Nautical Affordances for Walking

A DISSERTATION

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Abstract

I investigated the perception of affordance that emerge from dynamic aspects of humans (lateral oscillations of the body during walking) and the environment (angular motion of the ground). I chose to focus on the ways in which motion of ships at sea may influence how humans detect their affordances. Humans going out to sea for thousands of years, yet very little research has addressed perception and action at sea. I conducted several affordance experiments at sea to begin filling the large gap in human movement literature. I chose to investigate the affordance of walking on the deck within the confines of a pathway. In Experiment 1, I asked seasoned mariners to estimate their ability to walk within a set pathway. Upon completion of these judgments, the mariners were then asked to perform the walking task. The results showed that mariners' judgments were accurate. In Experiment 2, I built off of this success, repeating the same design across daily changes in ship angular motion. Judgments accurately reflected these daily changes. Finally, in Experiments 3 and 4, I took a different approach. While the two previous experiments utilized the natural ship motion (environmental factor) to change the affordance, in Experiments 3 and 4 I used weights added to the participant (animal factor) to manipulate affordances for walking. I first established that added weight influenced affordance judgments on land. I then found similar effects on a ship at sea. Taken together, my experiments expand our understanding of perceptual sensitivity to affordances that arise from dynamic properties in the animal-environment system. Additionally, many implications concerning nautical performance and safety can be gleaned from this study.

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CHAPTER I: Introduction and Literature Review

Humans have been traveling by sea for thousands of years. A ship is moved by the surface motion of the sea, principally waves, that is, surface motions created by local winds, and swell, that is, surface motions created by distant winds. Waves and swell cause oscillatory motion of ships. These motions are complex and pose considerable challenges to the bodily control of everyone on board. Despite our long experience at sea, these multitudes of motions from every angle can provide quite a challenge to both experienced mariners and novices alike. Interestingly, the exploration of human movement at sea has long been ignored in the scientific fields. Only in recent years has nautical movement been investigated from a kinesiological perspective, and this basic research has only hinted at the complex nature of movements at sea.

The theory of affordances is particularly apt in describing how the human and dynamic nature of the ocean interact, as it focuses on the emergence of possibilities as a result of the relationship of the environment and the animal (Gibson, 1979). Despite the clear application of affordance theory to nautical locomotion, no study has been conducted on the subject. Therefore, in this dissertation research I investigated nautical affordances over a series of experiments that provided insight into how these affordances can be influenced by changes in the environment and in the animal.

What are Affordances?

To fully understand the reasoning behind my experiments, one must first understand the concept of affordances. Introduced by Gibson (1979), an affordance is an opportunity for action that arises from the properties of the animal and its environment.

Affordances can be created (the building of a road can afford travel through previously impassable mountains), altered (adding a handrail can make a gap possible to cross), or destroyed (natural disasters can make previously passable trails unpassable). Affordances are rooted in physical, measurable features of the environment and the animal, shaping how animals adapt and behave in specific environments. For example, the action of walking can only occur is the environment allows it (smooth sidewalk verses steep mountainside) and the properties of the animal allow it (use of legs, muscle tone, etc.). By nature, these affordances inform the animal of possible future actions, and the completed actions then provide additional information to inform other future actions. This prospective-reactive behavior loop is known as perception-action coupling (Adolph, Eppler, Marin, Weise, & Clearfield, 2000, p. 442), which allows animals to constantly fine-tune their behaviors in response to changes in their environments. “Adaptive control” (p. 422) is the real-time process that utilizes this coupling to ensure that action is suited for the local conditions prospectively. The dynamic nature of these action capabilities allows the successful navigation of animals through their environment. Therefore, affordances are possibilities for action that, when acted upon, allow the animal to fine-tune their behaviors and successfully navigate.

The Existence of Affordances

Affordances exist as properties of reality, not as a concept inside one’s head. The ontological reality of affordances has been demonstrated, analytically. One of the best-known of these demonstrations was provided by Warren (1984). The affordance was that of the “climbability” of various risers of different heights. Specifically, the affordance of stair climbing is dependent on the individual's leg length in relation to the height of the stairs (Figure 1).

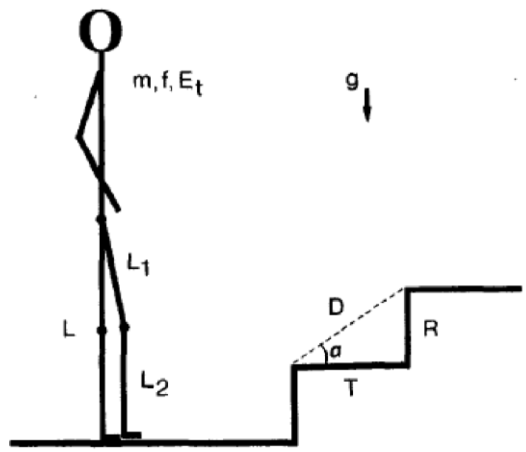

Fig. 1. Variables of the climber-stair system: R = riser height, T = tread depth, D = stair diagonal, a = pitch, g = gravitational acceleration, L = leg. length, L1 = thigh length, L2 = lower leg length, m = body mass, f = step frequency, E, = energy expenditure per unit time. (Warren, 1984, p.685)

Because the possibility for stair climbing is limited by the physical properties of the human and the stairs, a "critical point" emerges in which the action of bipedal climbing is no longer possible (p. 687). This "critical point" is a mathematical ratio based on the properties of the animal and environment: the maximum step a human can climb is 88% of their leg length. Later research into this same affordance (Konczak, Meeuwsen, & Cress, 1992) indicated that several other factors also affect the affordance of climability, such as hip flexibility and leg strength.

As defined by Mark, Balliet, Craver, Douglas, and Fox (1990), the critical point depends on "a lawful relationship among the requires of the action, the individual's body scale (size and proportions) and biodynamic capabilities…" (p. 326). This statement is critical for the study of affordances, for it is this lawful (mathematical) relationship that allows us to conduct research. Mark et al. (1990) measured the actual maximum sitting height of each participant, which would later be manipulated by adding blocks to the bottom of the participants' shoes. In this study, the affordance (sitting on a chair) was altered by the blocks; the additional height meant that the ratio changed, and therefore the participant could sit on a higher sitting surface. Adolph (1995) also calculated a "critical point" for a different population: infants. In this study, the affordance for safely traversing a ramp was explored. The results indicated that more adult-like proportions were associated with better walking skills, which was also associated with different critical boundaries for slope ascent/descent. Again, differences in the animal (proportions) changed the possible affordances available in a specific environment (sloped ramp).

These two studies highlight a key component of affordances: they are based in a mathematical ratio. Affordances are not mental processes or are limited to the realms of the mind but are physically definable. They exist in our physical world, as the walk-ability and the climb-ability and the grab-ability of our surroundings. However, affordances are also subjective. That is to say, affordances exist physically, but are also affected by animals who exhibit subjectivity. No two animals will have identical affordance variables, like the variables seen in Fig. 1. Warren (1984) illuminated the issue of subjectivity by utilizing "tall" and "short" participant groups in his experiments. Interestingly, these groups were able to detect that there were differences in their abilities: the tall group indicating they could step on taller risers than the short group (Figure 2), and this was indeed supported by their performance. While the

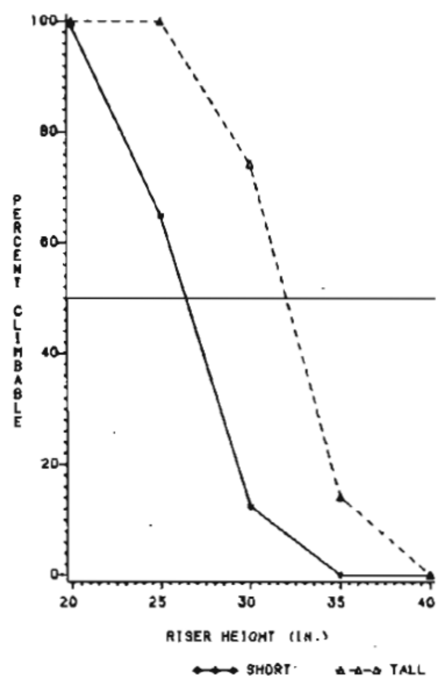

Fig. 2. Mean percentage of "climbable" judgments as a function of riser height for each group. (Warren, 1984, p.689)

affordance of climbing stairs is available to most able-bodied adults, there are variations in the equation of this affordance due to the nature of the physical variations that occur in the animal. Therefore, while affordances are objective (derived from mathematical ratios), they are also subjective (dependent on the characteristics of the individual).

Perceiving the Affordance

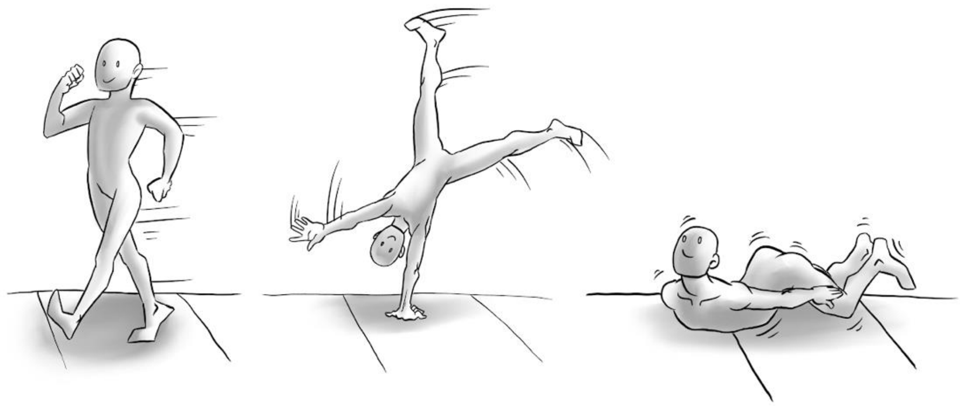

Fig. 3. Possibilities for action dependent on properties of the animal and the environment. A sidewalk affords walking, cartwheeling, or wiggling. These affordances exist whether the animal perceives them or not.

Figure 3 shows several affordances that are available to the same person. However, the fact that an action is possible (i.e., is afforded), does not necessarily mean that every affordance will be perceived. Multiple affordances are available at any time even if they are not detected. The possibility for walking may be present, as well as the possibility to cartwheel or even wiggle, even though one may not even consider wiggling for locomotion. There are thousands of possibilities for action at any time, but many of these possibilities are not considered. Affordances can be extremely complex and massive, involving many different scales at the same time, making how affordances are perceived a separate topic of interest.

In Warren's (1984) Experiment 1, the stair height was varied in an attempt to influence the perceived "climability" of the stair height. Participants were shown photographs of a wooden stairway that was adjusted into five different step heights. For each photograph, the participants were asked to judge whether they could climb the stairs. Participants' responses followed a predictable ratio that is dependent on their leg length in comparison to the stair height (Figure 4). This ratio is riser height divided by stair length = 0.88, meaning the maximum height of a stair that can be climbed bipedally must be .88 of the participant's leg length. This result indicates that participants were sensitive to the presence of the affordance, and that perception was tied to their portion of the ration (leg length).

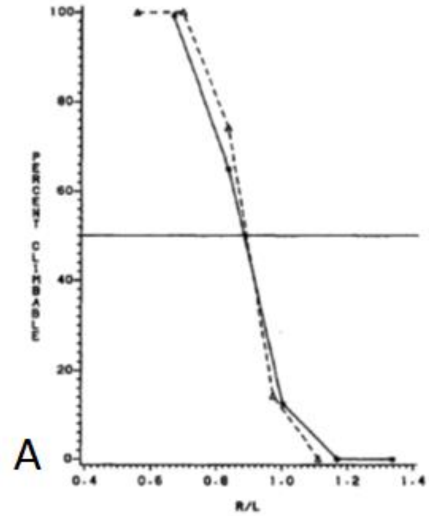

Fig. 4. Intrinsic plot: mean percentage of "climbable" judgments as a function of R/L for each group.

Another cornerstone of affordance research is the study of Mark et al. (1990). This study investigated whether adults could "retune" their affordances after platforms were added to their shoes. Mark et al. (1990) measured the actual maximum sitting heights for participants and then added 10 cm blocks to the bottom of the participants' shoes. In this case, the independent variables were the shoe condition (blocks or no blocks) and exploration condition (walking, no walking, or peephole). The dependent variable was judgments of maximum sitting height, in which a height adjustable chair provided various sitting heights. By altering both sides of the pi ratio for sitting (leg length and chair height), the affordance for sitting was changed and therefore participant judgments about their capabilities should be altered. Again, the affordance was changed, and the perception of this change was the focus of the study.

In Experiment 1 of Mark et al. (1990), participants were asked to walk around the room and then return to a set location to provide judgments. Participants in the block condition gave initially inaccurate judgments of their maximum sitting height that became more accurate over time. It was hypothesized that the exploratory behavior (walking) provided enough information to allow the participant to slowly hone in on the correct judgment. In Experiment 2, participants were instructed to not walk but rather stay in place. This behavior also provided enough information for the block condition participants to slowly improve their judgments, which indicates that postural adjustments and head movements provided enough information to help the participant understand how the blocks altered their affordances. However, Experiment 3 limited exploration drastically and participants were forced to view the sitting surface height through a small peephole. Participants in both the block and no-block conditions struggled to accurately perceive their maximum sitting height. The perception of the affordance was stunted due to a lack of exploratory behavior. These results may be interpreted that movements allowed participants to better perceive their altered affordances, which is further supported by the large amount of variability and error in the peephole condition.

Regia-Corte and Wagman (2008), had participants wear a backpack-type apparatus that changed the amount and distribution of mass. There were three conditions: high mass, low mass, or no mass. These sudden changes in weight resemble the adjustments of height made in Mark et al. (1990), with similar results: participants were able to perceive the changes in their affordances (in this case, ability to stand on an inclined surface) brought on by a discrete change to their physical properties (in this case, mass and mass distribution).

Chen, Tsai, & Wu (2014) investigated the perception of affordances in children at risk for developmental coordination disorder (DCD). The at-risk group made less accurate judgments of their capabilities than the normally developing group, indicating a difference between how affordances are perceived by those with developmental coordination disorder. This study indicates, among other things, that the perception of an affordance is separate from the existence of the affordance. An affordance can exist whether or not the animal has perceived it, and it appears that individuals who struggle (such as those with DCD) may have impaired perception of their affordances.

All the affordances discussed above were considered "static." That is, physical properties of the animal (weight, height, etc.) did not fluctuate over a short period of time. During each trial, in each experiment, the changes to the affordance (block height, stair height, added weight) did not change during the trail. While these experiments do provide us with the basics of affordances, there is an environment in which affordances are subject to constant fluctuation: the ocean.

Why Nautical?

At this point in time, our understanding of affordances has been shaped by studies conducted in stable environments. Few environments change constantly, but some examples do exist, with the main example being the ocean. There is no dearth of available ships and nautical opportunities to study, especially with the large variety of people who pursue ocean travel (professional mariners vs. novices, young vs. old, etc.).

The dynamic nature of the ocean environment provides a unique laboratory setting that moves in six degrees of movement which is extremely difficult and expensive to replicate on land. It is entirely possible that dynamic properties of the sea may influence affordances in ways not seen on land, influencing how the ecological community understands the traditional definition of affordances. The possibility for critical insight into the theory of affordances is there, but currently there is little to no research on nautical human behavior. Simply stated, our fundamental understanding of how the theory of affordances works may be dramatically influenced by conducting research in this accessible but ignored environment.

The possible additions to basic research are clear. However, there is also the possibility for applied research outcomes as well. The cruise industry is a multi-billion dollar per year industry, and injuries do occur onboard. One study, Dahl (2010), indicated that 663 injuries occurred over a period of three years on a single cruise ship, with 12.5% of these injuries being considered serious. This cruise ship catered to the older demographic, with a median age of 68.5 years of age. Interestingly, "the most frequent accident location aboard was the victim's cabin (20.1%), followed by the bathroom (13.4%), outdoor sports areas (9%), and open decks (9%)" (p. 3). Those who are injured aboard are not injured partaking in physical sports, but rather in unsuspecting places such as one's cabin. A total of 80.5% of accidents occurred due to slips, trips, falls, or being hit by something or someone, and alcohol was recorded in only seven total injuries. Poor weather contributed to only 22 injuries.

Dahl (2010) concluded that "passenger injuries contribute considerably to the workload of the medical team aboard. A well-equipped, competent medical staff will effectively treat most injuries aboard and thus reduce the number of costly and inconvenient helicopter evacuations, ship diversions, port referrals, and medical disembarkations" (p. 1). These statistics on this one cruise ship clearly highlight the potential applications that studying movement at sea can have. How can nautical movement research influence cruise ship design to reduce injuries? What can be changed to create a safer experience? Do military nautical vessels have similar problems? This study did not mention injuries to staff, who are working in the kitchens and around heavy equipment that the passengers do not have access to. Clearly this field would benefit from a better understanding of human movement at sea.

Previous Nautical Research

Humans have been traversing the seas for thousands of years, but research of motion at sea has only began in recent years. Even the presence of "sea legs," a well-known phenomenon, has never been quantitatively defined. While kinesiological research is becoming more common at sea, the utilization of affordances in this environment are nonexistent. Stoffregen, Chen, Varlet, Alcantara, & Bardy (2013) describe sea legs as "the process by which we adapt bodily control to life at sea" (p.1). Novices typically adapt to sea movement in a period of a few hours to a few days (Stevens & Parsons, 2002), providing a window to study the adaptiveness of affordance perception. With the dynamic nature of the ocean and the obvious gaps in the literature, one would imagine that research in this ever-changing environment would be more popular among scientists. Despite this lack of interest in nautical affordances, the research collected to this point has been sparse.

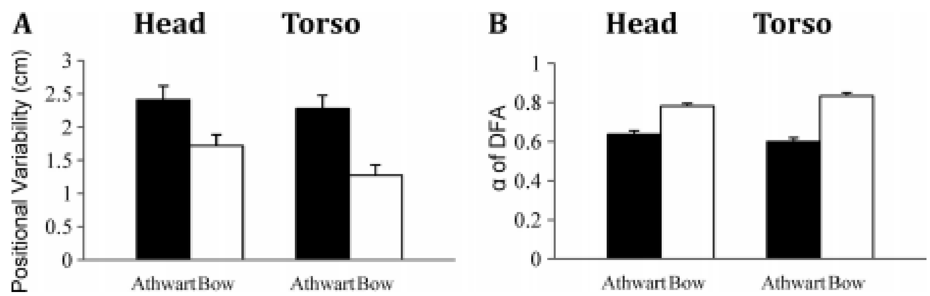

Fig. 5. Statistically significant effects of torso orientation on movement of the head and torso. **A**. Positional variability. **B.** Dynamics (∝ of DFA). Athwart = Torso oriented toward the ship's port side. Bow = Torso oriented toward the bow. The error bars represent standard error.

Chen and Stoffregen (2012) investigated the relations of postural activity at sea and performance in a pointing task. This was a simple experiment, which utilized one of the most basic of movement activities, heavily supported the idea that postural activity can be heavily influenced by torso direction at sea. Participants were instructed to aim a laser pointer at small (2 cm diameter) and large (4 cm diameter) targets while facing either the bow or athwart and additionally facing the target forward or over their shoulder for a total of eight trials. In terms of postural activity, all the independent factors listed above had an influence. This simply means that facing one direction and then turning 90 degrees to face another direction has tangible effects on postural sway, which is indicated in Figure 5. As seen in Figure 5A, positional variability was greater in both the head and torso when the torso was oriented in the athwart direction than when the torso was oriented towards the fore-aft direction. Additionally, orientation in the athwart direction resulted in reduced self-similarity in both the torso and the head (Figure 5B). The manipulation of orientation on the ship "influenced the magnitude and the dynamics of movement of both the head and the torso" (p. 208). This strongly indicates that additional behaviors, such as walking, would also be influenced by orientation. The natural asymmetry in ship directions (i.e., ships are longer than they are wide, such that roll typically is greater than pitch) is an experimental design that has repeatedly been utilized (Chen and Stoffregen, 2012; Haaland, Kaipust, Wang, Stergiou, & Stoffregen, 2015; Stoffregen et al., 2013).

Haaland et al. (2015) studied gait on a ship at sea. The effects of walking direction on temporal parameters of gait were investigated. The authors utilized straight pathways inside the ship that were parallel to the ship's fore-aft and athwart directions. Participants (experienced mariners) were asked to walk back and forth on these pathways while wearing electric contact switches on the bottom of their shoes. The results indicated that variability in stride time differed between direction (fore-aft mean = 0.10 s; athwart mean = 0.28 s). This effect may be the first demonstration that ship motion affects the quantitative kinematics of gait. One may suspect from these results that the participants were detecting information that led to direction-specific patterns of gait kinematics. It may be that participants detected the direction-specific effects of ship motion on affordances for walking.

Naval Engineering

Most ships are longer than they are wide. This design creates differences in angular motion and, in conjunction with the six degrees of freedom of motion, should influence the walking capabilities of anyone onboard (Figure 6). While the deck itself remains static, the sea influences the direction and speed of ship movement. As stated above, the oblong shape of a ship influences the amount of angular ship motion experienced as a factor of direction. When walking in the athwart direction, pitch tends to affect side-to-side oscillation of the body. When walking in the fore-aft direction, lateral oscillation tends to be affected roll. Because ship motion is generally stronger in roll than in pitch, side-to-side oscillation at sea tends to be greater (and more variable) in the fore-aft direction. It should be noted that this movement is often minimized on larger cruise vessels, which often utilize heavy stabilizers to reduce the overall oscillations.

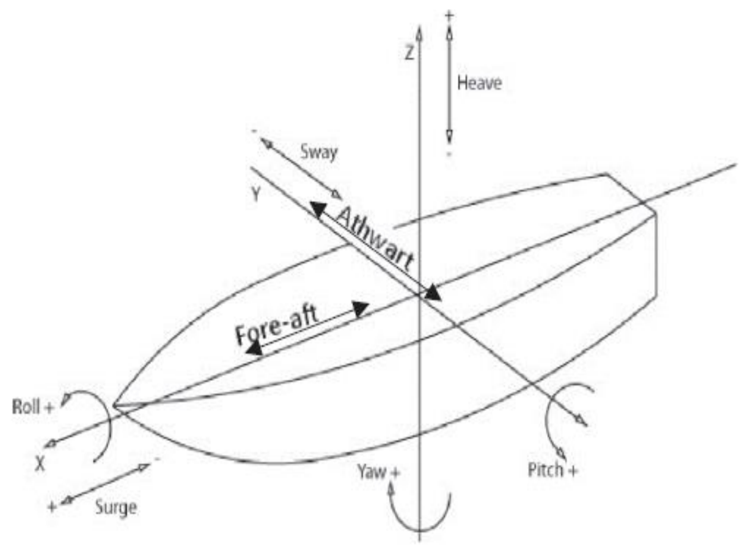

Fig. 6. Ship motion occurs in six degrees of freedom. Angular ship motion comprises roll, pitch, and yaw, while translational ship motion comprises surge, sway, and heave. The figure also indicates the ship's fore-aft and athwart axes.

Conveniently, this ship motion occurs naturally and with regular variation, which allows for similar, reliable environmental changes during the day. This predictable motion of the ship allows research to be conducted with relative confidence that each participant will experience similar movement over the course of a day. Thus, despite the dynamic properties of the environment, it is possible to "standardize" what the participant is exposed to. It is also possible to obtain data on the ship's angular motion, which can be then analyzed to quantify the relative magnitude of roll and pitch motion.

Differential ship motion in pitch and roll creates challenges the physical behavior of anyone who sets foot on deck. How humans perceive their affordances in these challenging environments in comparison to the actual performance of the same affordance is extremely important, as these perceptions of their environment inform humans of potential successful actions and therefore influence behavior. Even basic research in this dynamic environment would provide insight into applied research topics, which could further inform maritime work policies. Despite this obvious motivation, nautical research is few and far between.

The Present Study

Motivations

Affordance theory is well suited for nautical research due to its focus on the impact of the environment on the outcome behavior. That is, since the definition includes a ratio, parts of the ratio can be manipulated to produce a predictable outcome that is consistent with the constraints of the affordance. As discussed in the previous section *Naval Engineering*, there is a natural discrepancy in ship angular motion as a result of the ship's design (i.e., roll typically is greater than pitch), which was utilized by Haaland et al. (2015), Chen & Stoffregen (2012), and Stoffregen et al. (2013). These differences in direction-based motion were utilized in my own research, as they are present on any research vessel. Changes in sway and gait at sea are positive signs for changes in affordances, which could be easily investigated by recreating classic affordance research in such conditions. Additionally, the use of methods like those described in Haaland et al. (2015) could be utilized to study the affordances of walking at sea. However, these previous studies utilize only environmental properties in their nautical experiments. One way to create sudden changes in the property of the animal is the addition of weights, as Regina-Corte and Wagman (2008) did. The change in weight distribution changed the perception of the affordance of standing on a slope. In the context of walking, one might relate this to the use of a long pole often used by tightrope walkers: changes in weight distribution affect balance. By distributing weight across several different points on the body, the participants would have to detect changes in their center of mass to successfully judge their future performance of walking within a narrow path.

Based off the walking design seen in Haaland et al. (2015), I proposed a series of nautical studies as a successor to the in Mark et al. (1990) and Warren (1984) affordance research. This entailed the use of judgments of the participant's perceived affordances for walking that is followed by performance trials. Haaland et al. (2015) and Chen and Stoffregen (2012) took advantage of the natural discrepancy between ship directions and the resulting variations in pitch and roll, which I predicted would also influence the nautical affordances for walking that are investigated in my proposed study. Unlike Haaland et al. (2015), I proposed these experiments take place on the deck, where there is ample room for both walking conditions. Additionally, the utilization of weights for sudden change in the affordances of the participant (Mark et al., 1990) would provide a logical expansion of the previous experiments.

Purpose of the Study

The purpose of my study was to further our knowledge of human perception, specifically the perception of affordances for walking that is influenced by the motion of a ship at sea. Many naval institutions have longed for a more efficient crew, free from injury that often befalls those who venture out to sea. By taking these first introductory steps into understanding nautical affordances, I have laid the foundation for future research in kinesiology, human factors, engineering, and other fields that have a hand in ocean travel. Until now, research concerning the basics of motor control in nautical environments has been neglected, despite the unique setting that nautical environments provide. A better understanding of how humans interact with the ever-changing environment also provides insight into human motion on land and in similarly dynamic environments, such as space. However, before such advancements in science can occur, the basics must be further investigated to their fullest. My experiments help fill the gap in affordance literature and general nautical literature that has been unfortunately neglected, despite the numerous safety and efficiency problems that could be tackled with such information.

Significance

Safety at sea is a major concern for all nautical groups and understanding how one judges (or misjudges) affordances may lead the way for improvements in performance and safety at sea. By understanding the process in which humans adapt to changes in their affordances in a "dynamic" context, safety measures can be designed to further enhance safe decision making. Another benefit of nautical research is that it provides me with the unique opportunity to explore human movement and behavior in such unique conditions that may impact our understanding of other modes of transportation. Space will eventually become readily available to us, and the understanding of how humans adapt and traverse such unique environments will be important.

While the identification of the affordances for walking on a ship at sea will not completely explain what it means to get one's "sea legs", my research helps fill a large gap in the literature concerning dynamic environments and affordances. My work is the first study of nautical affordances, which means there is an entire field of research that has not been touched. In terms of general affordance literature, my research is meaningful due to its unique utilization of a dynamic environment that is rarely replicated on land. Most extant studies of affordance perception have focused on situations in which the relevant properties of the environment either 1) were static (e.g., Warren, 1984), 2) changed only in a discrete fashion (e.g., Mark et al., 1990), or 3) changed in ways that did not affect affordances for whole body activity (e.g., Oudejans, Micheals, Bakker, & Dolné, 1996). The dynamic environment in which I conducted this research brings unique understanding to the literature surrounding the adaptive process of perception and action. Furthermore, my research expands our knowledge surrounding the affordance theory by providing evidence of affordances even in constantly changing environments.

Therefore, my investigation of the affordance for walking, which investigates the relationships between sea condition, experience, ship design, and affordance comprehension provides a unique insight into the adaptable usage of affordances. Finally, controlled variations in motion of the ground surface can be utilized to address how walking affordances can be influenced by surface motion. While a ship's motion cannot be controlled directly, I exert de facto control by conducting testing on different days that are characterized by different sea states.

Goals and Hypotheses

Based on the previously reviewed literature, I proposed a series of experiments on affordances for walking on ships at sea. In these experiments, my goals were to 1) investigate how the walking direction on the deck of a ship influences participant walking affordances, 2) study how sea condition influences affordances for walking, 3) study how sudden changes to the participant's properties influence the affordances for walking. I chose experienced mariners for the majority of our participants owing to the novelty of our study. To the best of our knowledge, no previous experimental studies have addressed the possibility that humans might be sensitive to the moment-to-moment changes in constraints that characterize affordances for bodily activity on ships at sea. An important goal of our study was, therefore, to ascertain whether any such capability existed, and for this reason it seems prudent to use as participants individuals who would have the greatest possible likelihood of exhibiting sensitivity to affordances of this kind. With these goals in mind, the following hypotheses were made:

H1: Participants will be prospectively sensitive to the changes in affordances for walking along a narrow path caused by the differences in angular motion due to walking direction.

H2: Participants will be prospectively sensitive to the changes in affordances for walking along a narrow path caused by changes in angular motion when pitch is greater than roll.

H3: Participants will be prospectively sensitive to the changes in affordances for walking along a narrow path caused by the addition of weights.

H4: Accuracy of judgments would increase across judgment trials without walking practice or feedback with the addition of weights.

CHAPTER II: Dynamic perception of dynamic affordances: walking on a ship at sea

Introduction

Affordances are behaviors that are available to a given organism (or group of organisms) in a given environment (Gibson 1979, 1987). Affordances emerge from relations between properties of the organism (or organisms) and properties of the environment (Stoffregen, 2003). Affordances are based upon dynamic action capabilities. One example is running to catch a fly ball (Oudejans et al., 1996), which is dependent upon the ratio of time available (before the ball hits the ground) and time required for the perceiver/actor to arrive at the impact point. Another example is crossing the street in traffic (Lee, Young, & McLaughlin, 1984; Plumert, Kearney, & Cremer, 2004), which is dependent upon the ratio of time available (between successive cars) and the time needed to cross.

One common human behavior is locomotion, such as walking, running, or rolling in a wheelchair. Opportunities for locomotion emerge from relations between properties of the environment and properties of the person. Many studies have examined the opportunity to walk, run, or roll through apertures. Passage through an aperture is afforded when the width and height of the aperture are greater than the (static or dynamic) width and height of the person, and participants are able to differentiate apertures that afford passage from those that do not (e.g., Franchak, Celano, & Adolph, 2012; Higuchi, Takada, Matsuura, & Imanaka, 2004, 2011; Yu, Bardy, & Stoffregen, 2011). Similarly, locomotion is afforded when the ground surface is rigid, that is, when it resists the forces that are applied by the walker (or crawler). Infants can differentiate surfaces that are sufficiently rigid to support locomotion from those that are not (e.g., Gibson et al., 1987; cf. Berger, Adolph, & Lobo, 2005).

We evaluated the perception of an affordance for walking that was influenced by motion of a ship at sea. Ocean swells and waves give rise to oscillatory ship motion in six degrees of freedom (DOF); three of rotation (roll, pitch, and yaw), and three of translation (surge, sway, and heave); (Chapter 1, Fig. 1). Ship motion typically is concentrated below 0.2 Hz (e.g., Stoffregen, Villard, & Yu, 2009). This highly complex motion contrasts with motion within a single DOF, which characterizes many laboratory research devices, including treadmills, moving platform posturography (e.g., Nashner and McCollum, 1985), and many whole-body motion devices that move seated participants either vertically (O'Hanlon and McCauley, 1974) or horizontally (Nawayseh and Griffin, 2005). Some whole-body motion devices feature six DOF motion, but such devices typically are not large enough to suit the requirements of our study. For example, Dobie May, & Flanagan (2003) evaluated walking on a six DOF ship simulator, but the maximum walkable straight line path was 3 m.

The main purpose of walking is to move forward, but walking necessarily includes lateral oscillations of the body as weight shifts between the feet. In the present study, we identified an affordance that was influenced by relations between a dynamic property of the participant (the ability to modulate lateral oscillations in walking) and a dynamic property of the surface of support (angular motion of a ship at sea). Motion of the ground surface can influence walking. Common examples include walking the length of subway or train cars, and stepping onto or off of a moving walkway (of the kind commonly found in large airports), which often causes momentary but very noticeable changes in gait. This example is convenient because many readers will be familiar with it from personal experience. However, it is of limited relevance to the present study, in part because moving platforms typically are limited in the DOF of movement, as compared with ships, where gait is constrained by the complex, six DOF motion of ships at sea.

Ship motion induces global changes in gait that are sufficiently general that they can be seen by casual observers; sailors have a “rolling gait” that persists for several hours after return to land (Stevens and Parsons, 2002). Given these effects, controlled variations in motion of the ground surface might be used to address the perception of how walking affordances can be influenced by surface motion. Yet, generally the experimenter cannot exercise control over ship motion. Conveniently, regular variations in ship motion occur naturally, as a consequence of naval architecture. Generally, ships are longer than they are wide, and for this reason angular ship motion will tend to be greater in roll than in pitch. Ship motion in roll occurs around the ship’s fore-aft axis, while ship motion in pitch occurs around the ship’s athwart axis. At sea, the kinematics of upright stance are powerfully affected by facing fore-aft versus athwart (Chen and Stoffregen, 2012; Munafo, Wade, Stergiou, & Stoffregen, 2015; Varlet et al., 2014; Varlet, Bardy, Chen, Alcantara, & Stoffregen, 2015). In addition, in walking on a ship at sea the timing of footfalls differs between walking along the ship’s fore-aft versus athwart axes (Haaland et al., 2015). In the present study, we asked whether the fore-aft/athwart distinction would alter the distance that mariners could walk along a narrow path (i.e., the affordance for maintaining dynamic gait within a narrow path), and whether experienced mariners would be sensitive to these differences in a prospective manner.

That is, we asked whether experienced mariners would be sensitive to direction-specific affordances for locomotion.

When at rest (e.g., at the dock), the surface of the deck was the same in all directions. At sea, the static properties of the deck were unchanged, including its material substance, the way it reflected light, and its topography, or geographical layout. Yet at sea the deck was in motion, and this motion varied as a function of direction. Ship motion created a "force topography", or a dynamic topography. The way that the deck moved varied as a function of direction. Angular ship motion tends to influence gait as a function of direction. When walking athwartship (i.e., from port to starboard, and vice versa), ship motion in pitch tends to affect side-to-side oscillation of the body. When walking fore-aft (i.e., toward the bow, or stern), lateral oscillation tends to be affected by ship motion in roll. Because ship motion typically is greater in roll than in pitch, lateral oscillation at sea tends to be greater (and more variable) when walking fore-aft than when walking athwartship. Therefore, when asked to walk along a narrow path at sea, we predicted that performance would be better when walking athwart than when walking fore-aft.

We also predicted that experienced mariners would be sensitive to the differential effects of roll and pitch on gait, in general, and on lateral oscillation during gait, in particular. To test each of these predictions, we created narrow pathways on the open deck of a ship at sea. One pathway was parallel to the ship's long, or fore-aft axis, and the other was parallel to the ship's short, or athwart axis (see Fig.2). We expected that participants would be able to walk farther along the athwart path. Before assessing walking performance, however, we asked participants to judge how far they would be able to walk along each path. We expected these judgments to differ as a function of path direction (fore-aft vs. athwart), and we expected the difference in judgments to mirror the difference in actual walking performance.

In the laboratory, devices that permit the control of whole-body motion in multiple axes rarely are large enough to permit walking (for a rare example, see Dobie et al., 2003). By contrast, unfettered walking is common on ships at sea. We could not control the motion of the ship, but we were able to manipulate existing motion as an independent variable in our study.

Experiment 1

Methods

Participants

Our sample comprised 13 men and three women, ranging in age from 20 to 72 years (mean = 45.6 years), in height from 1.5 to 1.9 m (mean = 1.78 m) and in weight from 68 to 172 kg (mean = 88 kg), and with 2–38 years (mean = 18.5 years) experience working at sea. As part of the consent process, participants indicated that they suffered from no history of balance disorders, vestibular dysfunction, seizures, or dizziness. The experimental protocol was approved in advance by the University of Minnesota IRB.

Table 1 – Experiment 1

Participant Characteristics (n = 16)

Participant Number	Sex	Age	Height (cm)	Weight (kg)	BMI	Years at Sea
1	M	26	185	97.52	28.4	6
2	M	58	183	81.65	24.4	38
3	M	67	185	74.84	21.8	30
4	M	27	188	83.92	23.8	7
5	F	28	157	68.04	27.4	7
6	M	50	188	129.27	28.4	6
7	M	72	189	92.98	26.0	20
8	M	42	178	77.11	24.4	18
9	M	59	193	172.36	46.3	30
10	M	56	178	90.72	38.7	25
11	M	47	17	81.65	28.2	7
12	M	54	173	68.04	22.8	36
13	M	20	188	83.92	23.8	2
14	F	39	183	70.31	21.0	12
16	M	61	18	86.18	26.5	30
18	F	24	152	49.9	21.5	4

Setting

Testing was conducted on the R/V Thomas G. Thompson (Fig. 1) during a transit from Seattle, Washington to San Diego, California. The ship was 84 m long with a 16 m beam. It displaced 3500 tons and cruised at 12 knots.

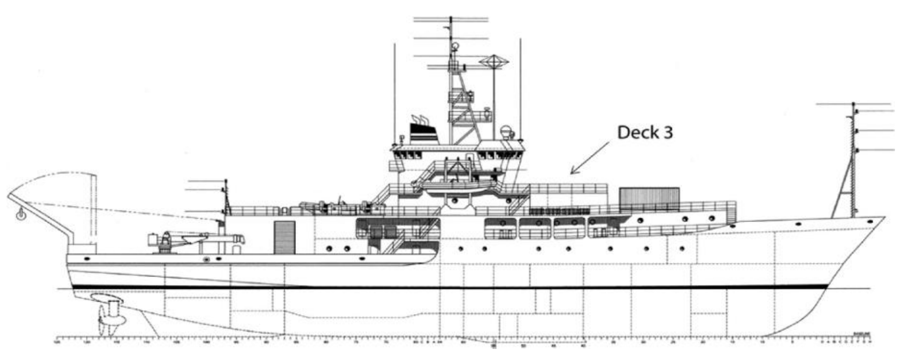

Fig. 1. The R/V Thomas G. Thompson. The arrow indicates the portion of Deck 3 on which the study was carried out.

Procedure

The ship departed Seattle on January 10, 2016 and arrived in San Diego on January 15. The data were collected on January 14, that is, on the fifth day of the voyage. Testing was conducted on the third deck of the ship, which was free from clutter (Fig. 2). Two pathways were created using clearly visible tape and were laid out on the long (fore-aft) and short (athwart) axes (Fig. 2). At the intersection of the two pathways was a starting plate, where participants stood with their feet on the taped lines. The purpose was to standardize foot position to reduce variation in the walking distance. Each path was 8.9 m long by 0.3 m wide. The length was the maximum that was available on the deck. The width was selected from informal testing so as to provide a moderate challenge given the ship motion on the day Experiment 1 was conducted.

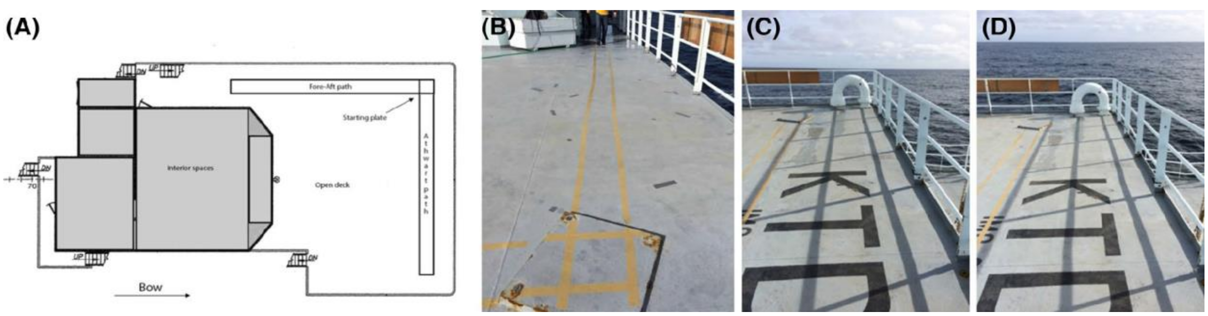

Fig. 2. a Overhead view of Deck 3, illustrating the placement of the walking paths. **b** Experimental setting, showing the starting plate, at the *bottom* of the photograph, and the fore-aft path. At *lower left*, the beginning of the athwart path is visible. **c**, **d** Roll motion on the day of testing. The camera is facing the port side; the bow is to the *right*. A portion of the athwart walking path is visible, ending at the starting plate. In **c**, the ship has rolled to starboard (the distant railing is elevated almost to the horizon), while in **d** the ship has rolled to port (the distant railing is well below the horizon)

Familiarization phase

Participants wore shoes in compliance with the ship regulations. Beginning on the marked starting plate, participants were asked to walk comfortably along the marked paths while ignoring the lines. "Keep your eyes on the end line (or plate), ignore the parallel lines, and walk comfortably to the end line (or plate)". Participants were required to walk out from the starting plate and back to the starting plate twice in the fore-aft and athwart directions. The purpose of the familiarization phase was not to provide practice at walking in different directions, which (presumably) participants had learned in their general experience, and in the preceding days of the voyage. Rather, the purpose was to provide practice at the traversing the marked paths that we had created for the study.

Judgment task

After familiarization, participants stood on the starting plate and were asked to estimate how far they could walk along each path without stepping on or over the lines. For each judgment trial, the participant was asked to look at the designated path and estimate "how far do you think you could walk along this path without stepping on or over the lines?". To indicate the participant's judgment, an experimenter stood near the participant, facing toward them while holding a marker (a 0.25 m length of a wooden 4 × 4). After a ready signal, the experimenter slowly walked backward along the path, and the participant indicated where the experimenter should place the marker to indicate their judgment. Each participant gave two judgments for each path, for a total of four judgments. Across trials, judgments alternated between paths, with odd-number participants beginning with the fore-aft path, and even-numbered participants beginning with the athwart path.

Performance (walking) task

After completing the judgment task, participants were asked to walk each of the paths. "Please do not look at your feet. Keep your eyes on the end line (or plate) and walk so as to avoid stepping on the lines." Each participant completed a total of 12 trials, comprising three laps (out and back) along each path (originating from the starting plate), with each length constituting one performance trial. If the participant stepped on or over the lines, it was classified as a "fault" and the performance length was recorded from this spot. Each of three experimenters watched for faults, with one experimenter on each side of the participant (following along) and one experimenter remained at the starting plate.

Data analysis

For judgments, we took the mean of the two judgments of the fore-aft path, and the mean of the two judgments in the athwart path. For performance trials, we took the mean of the six trials for the fore-aft path, and for the athwart path. Thus, for each participant we took four numbers (mean judgment fore-aft, mean judgment athwart, mean performance fore-aft, and mean performance athwart). We conducted inferential statistics on the means across participants. Using paired sample t tests, we compared judgments in the fore-aft versus athwart paths, and we compared performance in the fore-aft versus athwart paths. To evaluate the accuracy of judgments, we expressed judgments as a proportion of actual walking ability (judgment mean/performance mean) and compared these proportions for the fore-aft versus athwart paths.

Results

Data were collected on the 5th day of the transit, between 12:00 and 17:00. During data collection, the sea state was 3 on the Beaufort Scale (Beer, 1997), which corresponds to relatively mild ship motion (cf. Chen and Stoffregen, 2012; Stoffregen et al., 2013, 2009). Roll motion during data collection is illustrated in Fig. 3.

Anecdotally, there were more visible adjustments to posture and gait while walking the fore-aft path than while walking the athwart path. That is, participants more often disobeyed instructions (to walk comfortably) while walking fore-aft, making visible efforts to stay within the designated path. These anecdotal observations are consistent with the data, suggesting that keeping the feet inside the path lines was more challenging along the fore-aft path than along the athwart path.

The results are summarized in Figure 3. Judgments differed between path directions: participants judged they could walk further along the athwart path than along the fore-aft path, t(15) = 3.52, p = .003. Performance also differed between the path directions: Participants walked further along the athwart path than along the fore-aft path, t(15) = 2.74, p = .015. The accuracy of judgments (mean judged walkable distance/mean actual walked distance) did not differ between the athwart path (mean proportion = 0.839, 95% CI 0.57 < mean < 0.97) and the fore-aft path (mean proportion = 0.775, 95% CI 0.50 < mean < 0.94), p = .98. Finally, the 95% confidence intervals reveal that, for both the fore aft and athwart paths judged walkable distance was less than actual walkable distance.

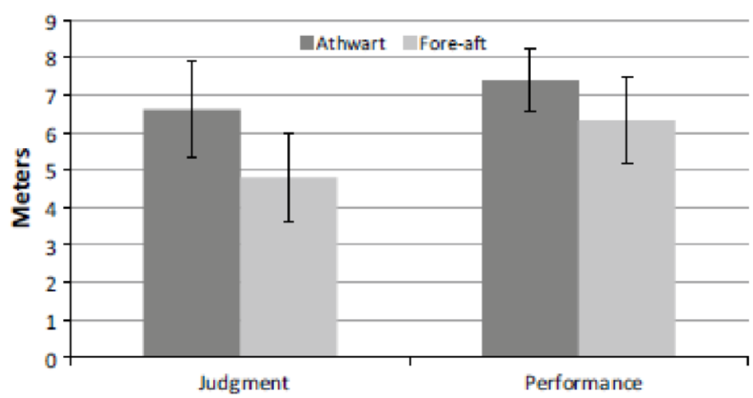

Fig.3. Statistically significant effects of direction (athwart vs. foreaft) on mean judgments of walkable distance, and on walking performance (mean distance actually walked). The *error bars* illustrate the 95% confidence interval of the mean

The visual appearance of the athwart path was the same in both directions; that is, when walking toward port as compared to when walking toward starboard. By contrast, the visual appearance of the fore-aft path differed as a function of direction. The "view" when walking toward the bow included the upper decks, effectively blocking much of the horizon (see Fig. 2), whereas when walking aft the horizon was plainly visible. Whether or not people look at it, simply having the horizon in view reduces the magnitude of standing body sway at sea (Mayo, Wade, & Stoffregen., 2011). For this reason, we felt it was appropriate to evaluate the possibility that walking performance might have differed as a function of walking direction along each of the two paths. Separately for each walking path, we used paired samples t tests to compare walking performance as a function of direction. For the athwart path, the effect of walking toward port versus starboard was not significant, $t = 1.09$, $p = .17$. For the fore-aft path, the effect of walking toward the bow versus the stern was not significant, $t = 0.60$, $p = .61$. That is, we found no evidence that walking performance was influenced by visual differences associated with walking in different directions along each path. A similar analysis for affordance judgments would have been meaningless, due to the fact that all judgments were made from the starting plate (Fig. 2a, b).

Discussion

On a ship at sea, participants (experienced maritime crewmembers) judged the distance that they could walk along narrow paths laid out on the open deck. One path was parallel with the ship's fore-aft axis, while the other was parallel with the ship's athwart axis. Under mild sea conditions, ship motion was greater in roll than in pitch, such that walking along the fore-aft axis was more challenging than walking along the ship's athwart axis. Participants judged that they could walk further along the athwart path than along the fore-aft path. Actual walking performance (evaluated after the completion of judgments) differed between the paths and was consistent with the judgments. The accuracy of judgments (relative to actual walking performance) did not differ between the two directions. We argue that differential ship motion in roll and pitch created differential affordances for locomotion along these two axes and that participants accurately detected these differences.

Walking performance

Actual walking performance differed between the fore-aft and athwart paths, that is, as a function of direction relative to the ship. The difference was in the expected direction (athwart performance > fore-aft performance), consistent with the hypothesis that the control of lateral oscillation was more greatly challenged when walking fore-aft than when walking athwart. This result is consistent with an earlier finding that step timing is more strongly affected by ship motion in roll than by ship motion in pitch (Haaland et al., 2015) and is consistent with similar effects in the context of standing body sway (Chen and Stoffregen, 2012; Munafo et al., 2015; Varlet et al., 2015). It is important to emphasize that these effects do not suggest a differential effect of roll versus pitch motion, as such. Rather, the observed effects arise from the fact that, in most cases the magnitude of motion is greater in roll than in pitch. Accordingly, we predict that the effects observed in our study could be replicated in a future study in which walking was always in the same direction (e.g., always athwartship), but the independent variable was changes in sea state (i.e., weather-dependent changes in the magnitude of angular ship motion).

Affordance judgments

We compared judgments of walking ability as a function of walking direction, relative to the ship. Judgments of walking ability along the fore-aft and athwart paths differed significantly, and the difference was in the expected direction (athwart judgments > fore-aft judgments). This result constitutes the first demonstration of sensitivity to affordances in the moving nautical setting. In our study, the same participants, standing in the same place on the same ship, varied their judgments of their own walking ability solely as a function of facing one direction rather than another, relative to the ship. The static properties of the deck did not vary as a function of direction; only its dynamic properties differed between fore-aft and athwart. Accordingly, our results are consistent with the hypothesis that participants were sensitive to these dynamic affordances.

We evaluated the accuracy of affordance judgments in terms of how judgments differed from actual performance (judged/actual). The accuracy of affordance judgments did not differ between the fore-aft and athwart paths. That is, the fact that ship motion was greater in roll than in pitch affected walking ability, and it affected judgments of walking ability, but it did not affect participants' ability to detect (judge) their walking ability. We take this overall pattern of results as evidence for the hypothesis that participants were sensitive to affordances, rather than basing their judgments on the magnitude of ship motion, as such.

For both directions, judged walkable distance was less than actual walkable distance, as shown by the fact that the 95% confidence intervals for the judged/actual ratio did not include 1.0. These differences might be interpreted as under-estimates which, in turn, could be interpreted in terms of a "safety margin" in affordance perception (cf. Warren and Whang, 1987). We view these interpretations as unlikely (cf. Franchak et al., 2012). In this study, we first familiarized participants with the walking paths by asking them to walk comfortably along each path. At this point, participants did not know that we would ask them to estimate their ability, and they did not know that we would (later) conduct a formal evaluation of their ability. During the judgment phase, we asked participants to judge walking ability if they were to walk comfortably (as they had done during the familiarization phase). We have no reason to believe that they did not follow our instructions when making judgments. By contrast, in evaluating actual walking ability, participants often did not honor our request to walk comfortably. Rather, in many cases, it was unmistakably clear that participants exerted active, deliberate (i.e., not "comfortable") efforts to keep their feet within the edges of the paths. That is, participants appeared to have judged their "comfortable walking ability", but to have actualized their "best" walking ability. If this is true, it would explain (indeed, it would predict) our finding that the ratio of judgments to performance was less than 1.0.

We did not include a control condition in which ship motion was absent. That is, we did not ask participants to judge affordances for walking in different directions under terrestrial conditions (i.e., at the dock). We took as given the idea that, in the absence of ship motion, participants would (correctly) perceive the distinction between walking along the fore-aft and athwart paths to be inconsequential, or meaningless. On land, when the ground is flat, rigid, and uniform (like the steel deck of our ship), facing and walking in one direction versus another is a meaningless variable; that is, it has no effect on affordances for walking (cf. Chen and Stoffregen, 2012). The rolling gait that typifies mariners on land rapidly fades (usually within 24 h) as they revert to their "land legs" (e.g., Stevens and Parsons, 2002). Before our voyage began, the ship had been in port for more than 2 weeks; thus, we can be certain that all participants had fully adjusted to terrestrial conditions. If it is accepted that participants could detect the fact that terrestrial affordances for locomotion were constant with respect to direction, then our results indicate sensitivity to the difference in affordances between land and sea, that is, to the fact that angular ship motion changes actual affordances for walking.

We chose experienced mariners as participants owing to the novelty of our study. To the best of our knowledge, no previous experimental studies have addressed the possibility that humans might be sensitive to the moment-to moment changes in constraints that characterize affordances for bodily activity on ships at sea. An important goal of our study was, therefore, to ascertain whether any such capability existed, and for this reason it seems prudent to use as participants individuals who would have the greatest possible likelihood of exhibiting sensitivity to affordances of this kind. Accordingly, it is likely that performance in our study was influenced by knowledge gleaned from our participants' long maritime experience. The success of our "best-case scenario" motivates future research in which it will be important to determine the nature of participants' sensitivity (e.g., the relative importance of immediate perceptual information versus responses acquired through previous experience), to evaluate changes that occur as participants adapt to life on a moving surface (that is, as they "get their sea legs"), and so on. Novice mariners rapidly adapt the kinematics of standing body sway to constraints arising from ship motion (Stoffregen et al., 2013). As part of this rapid adaptation, they appear to learn to use the nautical horizon as a referent for postural control (cf. Mayo et al., 2011). In future research, it will be important to track simultaneously changes in affordance perception and changes in the kinematics of posture and gait. Such coordinated monitoring can help us to understand how it is that participants learn about changes in affordances that emerge from the dynamics of ship motion (cf. Mark, 1987; Mark et al., 1990; Yu et al., 2011).

Conclusion

On a ship at sea, angular motion was greater in roll than in pitch. Ship motion in pitch would tend to affect lateral variation in gait when walking parallel to the ship's athwart axis, and ship motion in roll would tend to affect lateral variation in gait when walking parallel to the ship's fore aft axis. We asked experienced mariners to judge their ability to walk along defined paths that were aligned with the ship's fore-aft and athwart axes. Participants judged that they could walk further along the path that was aligned with the ship's athwart axis, that is, they judged that the affordance for walking was greater when walking was constrained by ship motion in pitch. Subsequent testing confirmed that actual walking ability (the distance that could be walked while remaining within the paths) was greater when walking along the athwart path than when walking along the fore-aft path. That is, in qualitative terms, the difference in mean judgments between the two path directions correctly mirrored the direction-specific difference in actual affordances. Finally, the accuracy of judgments (the ratio of judgments to measured ability) did not differ as a function of direction. Taken together, these results suggest that experienced mariners were sensitive to the fact that affordances for walking were differentially affected by ship motion in roll versus pitch. Behavior happens on vehicles, as well as on the surface of the Earth: cars, aircraft, surfboards, escalators, bicycles (e.g., Plumert et al., 2004), and ships at sea. Results from Experiment 1 motivates the study of affordances that are related to vehicular travel and, more generally, to the fact that behavior often is governed by forces other than (or in addition to) gravity (Stoffregen and Bardy, 2001; Stoffregen and Riccio, 1988; Stoffregen et al., 2013).

CHAPTER III: Adaptive perception of changes in affordances for walking on a ship at sea

Introduction

Affordances are possibilities for action that exist for a given animal in a given environment (Gibson, 1979; Stoffregen, 2003). For example, affordances for locomotion emerge from relations between properties of an animal and properties of the environment that allow for movement from place to place (e.g., Lee et al., 1984; Plumert, Kearney, Cremer, Recker, & Strutt, 2011). One type of locomotion is walking.

Walking necessarily includes lateral oscillations of the body as weight shifts between the feet. These lateral oscillations can influence relations between the animal and properties of the environment, that is, affordances. As one example, consider walking through doorways. One might think that the narrowest doorway that a person can walk through (without rotating their shoulders) would be equivalent to shoulder width, that is, the static width of the body. However, lateral oscillations in walking mean that doorways must be (at least) the "dynamic width" of the body in walking. People appear to be sensitive to this requirement: Judgments of the minimum width of a doorway for "walking through" are larger than static shoulder width but match very well with the dynamic width of the body in motion (Franchak et al., 2012B; cf. Higuchi, Takada, Matsuura, & Imanaka, 2004; Warren & Whang, 1987).

As an architectural feature, the width of any given doorway tends to be constant, such that in walking through doorways the person's own movement is the only dynamic aspect of the situation. Consequently, the ability to walk through a doorway emerges from the relation between the (static) width of the door and the (dynamic) width of the body. In other situations, relevant aspects of the environment may also be dynamic, such that affordances for walking emerge from relations between dynamic properties both of the person and of the environment. For example, motion of the ground surface can influence affordances for walking. Consider walking on subway or train cars, or stepping onto or off of moving walkways that often are found in large airports. These transitions often cause momentary but very noticeable changes in gait. In several studies, researchers have manipulated the fit between properties of perceiver and environment and have investigated perception of consequent changes in affordances for locomotion (e.g., Franchak et al., 2012; Higuchi, Cinelli, Greig, & Patla, 2006; Mark, 1987; Mark et al., 1990). However, in those studies, changes in affordances were relatively discrete. Such studies do not address (changes in) perception of affordances as a consequence of dynamic, continuous variation in the fit between perceiver and environment. Other studies have investigated the perception of affordances for the timing of locomotion; for example, walking or cycling through temporal gaps in automobile traffic (e.g., O'Neal et al., 2018; Plumert et al., 2011). Existing laboratory research has not addressed how motion of the support surface can influence locomotor affordances, or whether such influences can be perceived.

Affordances relating to ship motion

In the present study, we investigated perception of affordances that emerged from relations between dynamic properties of participants (their ability to modulate lateral oscillations in walking) and dynamic properties of the surface of support (angular motion of a ship at sea). Motion of the ocean's surface (swells and waves) gives rise to oscillatory ship motion in six degrees of freedom (df); three of rotation (roll, pitch, and yaw), and three of translation (surge, sway, and heave). These highly complex oscillations are concentrated below 0.2 Hz (e.g., Stoffregen, Villard, & Yu, 2009). Ship motion induces broad changes in gait that are sufficiently general that they can be seen by casual observers, such as the "rolling gait" that characterizes experienced mariners at sea (Stevens & Parsons, 2002). Given these effects, variations in ship motion might be used to investigate mariners' perception of how walking affordances are influenced by motion of the ground surface. Although the experimenter cannot generally exercise control over ship motion, regularities in naval architecture provide natural constraints on ship motion. In general, ships are longer than they are wide. Consequently, ship motion typically is greater in roll (about the ship's fore-aft, or front back axis) than in pitch (about the ship's athwart, or side to side, axis). At sea, the kinematics of upright stance differ dramatically when participants stand facing in different direction, such as fore-aft versus athwart (Chen & Stoffregen, 2012; Munafo et al., 2015; Varlet et al., 2014, 2015). In addition, in walking on a ship at sea the variability of stride time intervals differs between walking along the ship's fore-aft versus athwart axes (Haaland et al., 2015).

Walter, Wagman, Stergiou, Erkmen, and Stoffregen (2017) investigated sensitivity to affordances for walking on a ship at sea that arose solely from differential angular motion of the ship around its short (i.e., pitch) and long axes (i.e., roll). When walking athwartship (i.e., from port to starboard, and vice versa), side-to-side oscillation of the body in gait is influenced primarily by ship motion in pitch. When walking fore-aft (i.e., toward the bow, or stern), lateral oscillation is influenced primarily by ship motion in roll. In their study, as is typically the case on a ship at sea, roll was greater than pitch. Therefore, Walter et al., predicted that participants would be able to walk farther without stepping outside of the boundaries along a narrow path when walking athwart than when walking fore-aft. In addition, they predicted that experienced mariners would be sensitive to such direction-specific differences in walking ability, such that judgments of walking ability fore-aft versus athwartship would prospectively reflect differences in actual walking ability in these two directions. As predicted, participants judged that they could walk further along the athwart path than along the fore-aft path. Subsequent performance (actual walking along those same paths) was consistent with judged ability. The accuracy of judgments, that is, the ratio of judgments to performance, did not differ between directions.

Walter et al. (2017) interpreted these results as indicating that experienced mariners were prospectively sensitive to affordances for walking in different directions, where direction-specific differences in actual walking ability arose exclusively from the direction specific variations in the dynamic properties of ship motion, that is, in the relative magnitude of pitch and roll.

Changes in sea state qualitatively change affordances for gait

Walter et al. (2017) found that perception of affordances for walking on a ship at sea reflected the fact that ship motion is generally greater about the fore-aft axis than about the athwart axis (roll > pitch). However, while ship motion is largely a consequence of ship architecture, it also depends on sailing conditions. Under most sailing conditions (and as was the case in Walter et al., 2017), roll is greater than pitch. However, heading directly into a consistent, simple, unidirectional swell will tend to cause pitch to be greater than roll. The latter situation is rare. It might be that experienced mariners' knowledge of nautical walking is related to the static fact that the ship is longer than it is wide, or to expectations about the typical dynamic state in which pitch is greater than roll. Alternately, experienced mariners might be sensitive to how affordances for walking are influenced by variations in ship motion, which is influenced by both ship architecture and sailing conditions. In the present study, we asked whether perception of affordances for walking would reflect qualitative changes in ship motion occurring under different sailing conditions. Specifically, we asked whether perception of affordances for nautical walking would reflect constraints imposed by ship motion in the atypical case in which ship motion was greater in pitch than in roll.

Using a within-participants design, on a long cruise we selected for testing days that differed in sailing conditions such that they affected oscillatory ship motion. On one day (which happened to be the second day of testing), the relative magnitude of pitch and roll closely resembled Walter et al. (2017); that is, the more typical conditions in which roll > pitch. On this day, we expected to replicate the direction-specific effects that were reported by Walter et al. That is, we expected that participants would judge that they could walk farther along the athwart path than along the fore-aft path, and that judgments would accurately reflect actual performance. On the other day (which happened to be the first day of testing), the relative magnitudes of pitch and roll were reversed, such that pitch > roll. Under this condition, we predicted that participants would judge that they could walk further along the fore-aft path than on the athwart path, and that judgments would accurately reflect actual performance.

Under both patterns of ship motion (i.e., roll > pitch, and pitch > roll), we predicted that mean judgments of walking ability would differ across walking directions (i.e., walking fore-aft vs. walking athwartship). Our central prediction was that the nature of this difference would itself differ across ship motion conditions, such that the Ship Motion × Walking Direction interaction would be statistically significant. With respect to the accuracy of judgments, our prediction was that any changes in judgment accuracy would be independent of our predicted effects in mean judgments, and independent of any changes in the overall magnitude of ship motion.

We built on and expanded the work of Walter et al. (2017) not only by collecting data across sailing conditions that differentially affected oscillatory ship motion but also by quantitatively verifying such differences in ship motion. To confirm that roll actually exceeded pitch, Walter et al. relied upon the expert opinion of the ship's officers. In the present study, we obtained (and statistically analyzed) quantitative data on angular ship motion during the hours of data collection. These data allowed us to provide objective confirmation of the relative magnitude of angular ship motion in roll and pitch. This confirmation was critical for verification of our manipulation, across testing days, of the relative magnitude of pitch and roll.

Our study was conducted in the field, which necessarily reduced the level of experimental control that we could exert. We could not control the weather or the motion of the ship. However, following other field studies (Jacobs & Hawley, 2007; Mayo et al., 2011; Stevens & Parsons, 2002) we felt that the reduction in experimental control was necessary to address the issues at hand.

Experiment 2

Method

Participants

Our sample comprised 13 individuals (9 men and 4 women), ranging in age from 22 to 58 years (mean=39.15 years), in height from 1.45 to 1.91m (mean=1.76 m) and in weight from 54.43 to 92.99 kg (mean=75.3 kg), and with 1–40 years (mean=13.23 years) experience working at sea. Participants were working crew members who volunteered (with the Captain's permission), taking time off from their regular duties. None of these individuals had participated in our earlier study (Walter et al., 2017). As part of the consent process, participants indicated that they suffered from no history of balance disorders, vestibular dysfunction, seizures, or dizziness. The experimental protocol was approved in advance by the University of Minnesota IRB, and written informed consent was obtained from each participant. To ensure a large enough sample size to provide sufficient power reliably to exclude false rejection of the null hypothesis, we tested power (1-β) with the G*Power program (Faul, Erdfelder, Lang, & Buchner, 2007), using the a priori option and the effect size (0.81) for affordance judgments from Walter et al. (2017; n=16). Power analysis revealed a test power of 0.967 and suggested that a sample size of n=10 would be sufficient to achieve the desired effect size of 0.81.

Table 2 – Experiment 2
Participant Characteristics (n = 13)

Participant Number	Sex	Age	Height (cm)	Weight (kg)	BMI	Years at Sea
1	M	30	180.34	77.11	23.7	1
2	F	28	175.26	72.58	23.6	10
3	F	53	160.02	54.43	21.3	4
4	M	58	177.8	74.84	23.7	40
5	M	28	177.8	72.57	23.0	1
6	M	23	187.96	90.72	25.7	1
7	M	55	172.72	80.29	26.9	24
8	M	38	190.5	74.84	20.6	4
9	M	53	144.78	71.67	34.2	30
10	F	22	185.42	68.04	19.8	15
11	M	27	182.88	80.74	24.1	11
12	F	42	170.18	68.04	23.5	6
13	M	52	187.96	92.99	26.3	25

Setting

The study was conducted during a 16-day cruise aboard the R/V Atlantis, from Puntarenas, Costa Rica to Woods Hole Massachusetts, USA. The ship was 84m long with a 26m beam. It displaced 3500 tons, and cruised at 10–12 knots. The ship's equipment included an inertial measurement unit (IMU), a standard device that measured and recorded the ship's angular motion in each of the six df. From the IMU, we obtained data on the magnitude of roll and pitch. The IMU was sampled at 1 Hz. We analyzed ship motion in pitch and roll during the hours of data collection and summarized these data for each day of testing.

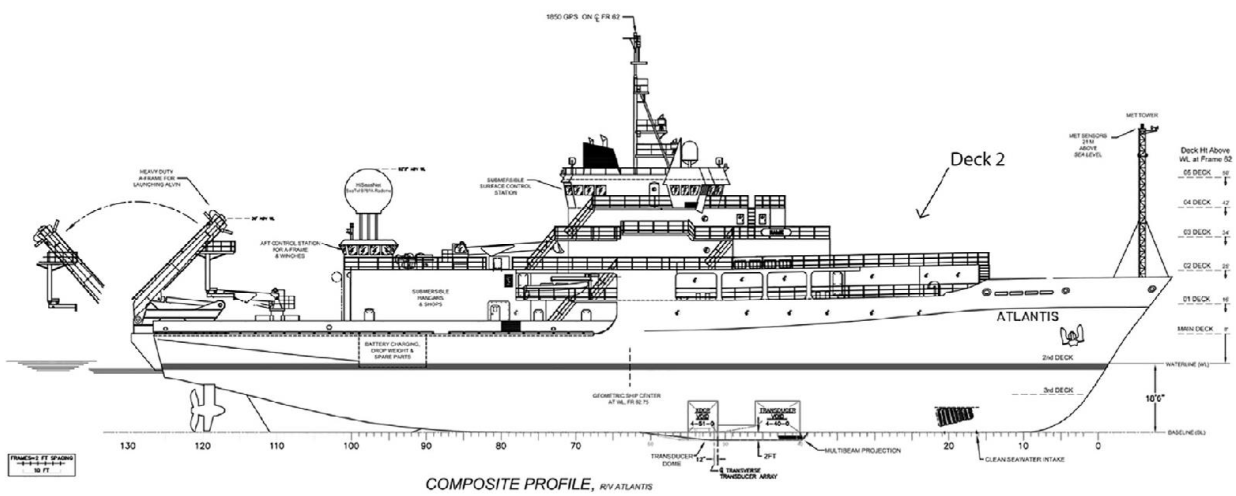

Fig. 1. The R/V Atlantis. The arrow indicates the portion of Deck 2 on which the study was carried out.

Procedure

The ship departed Puntarenas, Costa Rica on June 14, 2017 and arrived in Woods Hole Massachusetts, USA on June 30. The data were collected on Sunday June 18 and Sunday June 25. On each day, data were collected during full daylight, between 9:00 and 17:00. Testing was conducted on the second deck of the ship, which was free from clutter (Figs. 2 and 3). Two pathways (each 8.9m long×0.3m wide) were created at 90° using clearly visible tape. One pathway was marked along the long (fore-aft) axis, and the other was marked along the short (athwart) axis (Figs. 3 and 4). Judgment data were collected with the participant standing at the intersection of the two pathways. At this starting location, participants stood with their feet on the taped lines. The purpose was to standardize foot position to reduce variation in the walking distance. The length and width of each path was the same used by Walter et al. (2017). We used a within-participants design, in which each individual participated on both days. The methods and procedure were identical on the two testing days.

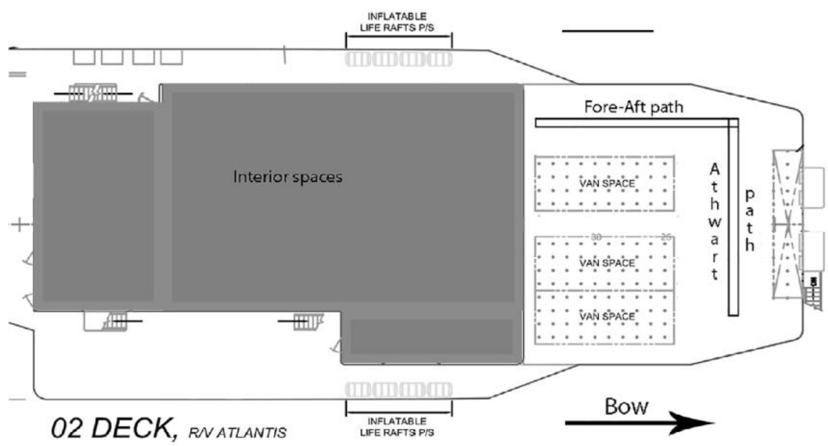

Fig. 2. Overhead view of the forward portion of Deck 2, illustrating the placement of the walking paths on the open deck.

Fig. 3. The athwart path (left) and the fore-aft path (right).

Familiarization phase

Participants wore shoes in compliance with ship regulations. Beginning at the paths' intersection, participants were asked to walk comfortably along the marked paths while ignoring the lines: "Keep your eyes on the end line, ignore the parallel lines, and walk comfortably to the end line". Participants were required to walk out and back twice along each of the paths. The purpose of the familiarization phase was to ensure that participants were comfortable traversing the marked paths that we had created, not to provide practice at walking in different directions. Given that participants were experienced mariners and that the first day of data collection was the 5th day of the voyage (such that participants had already performed thousands of steps in multiple directions all over the ship, cf. Chang et al., 2015), it is unlikely that the familiarization phase provided (additional) information that participants used in making their judgments. Also, in the familiarization phase participants walked the full length of the paths without interruption, without any feedback about performance, and (on the first day of testing) without knowing that we were going to ask them to judge their ability to walk within the paths.

Judgment task

After familiarization, participants stood at the path intersection and estimated how far they could walk along each path without stepping on or over the marked lines. On each trial, the participant was asked to look at the designated path and estimate "if you were walking comfortably, how far do you think you could walk along this path without stepping on or over the lines?" To report estimated distance, the participant instructed an experimenter where to place a marker (a 0.25m length of a wooden 4×4) along the path.

At the beginning of the trial, the experimenter stood near the participant, facing them, and slowly walked backward along the path until instructed to stop by the participant. Each participant gave two judgments for each path, for a total of four judgments. Across trials, judgments alternated between paths, with odd-number participants beginning with the fore-aft path, and even-numbered participants beginning with the athwart path.

Performance (walking) task

After completing the judgment task, participants were asked to walk comfortably along each of the paths: “Please do not look at your feet. Keep your eyes on the end of the path and walk so as to avoid stepping on the lines.” Each participant completed a total of 12 trials, comprising three laps (out and back) along each path (originating from the intersection point), with each length constituting one performance trial. If the participant stepped on or over the lines with any part of either foot, it was classified as a “fault” and the walked distance was recorded from the spot of the fault (see supplementary materials). Each of three experimenters watched for faults, with one experimenter on each side, walking behind so as to be able to monitor footfalls, and so as to be outside the participant’s field of view, and one experimenter remained at the starting point. Because ours was a field study in which the essential independent variable was a function of sea conditions, it was not possible for us to counter-balance the order of presentation of the different ship motion conditions.

Results

On the first testing day, the ship maintained a constant heading NE, directly into a consistent 2m swell from the NE. The sea state was 2.5 on the Beaufort Scale (Beer, 1997). On the second testing day, the ship maintained a constant heading north, which put it at a constant angle relative to a 2 m swell from the SW. The sea state was 4.0 on the Beaufort Scale. Anecdotally, during the familiarization phase participants' gait appeared to be natural, and comfortable. By contrast, during the walking performance trials (i.e., after completing judgments), participants often made visible efforts to maximize their performance, such as waving their arms or shortening their stride. That is, in their actual walking performance they appear to have tried to "walk as far as possible", rather than "walk comfortably". We did not exclude these trials from our analysis.

Ship motion

From raw data on ship motion, we computed the range of angular motion for each oscillation cycle. We used the findpeaks function in Matlab to identify the maximum excursion for each oscillation cycle, separately in pitch and roll. For each oscillation cycle, the difference between successive peaks was the range of motion for that cycle. We subjected these ranges to a 2×2 ANOVA with factors Days (Day 1 vs. Day 2) and Motion Direction (Pitch vs. Roll). In the ANOVA, the degrees of freedom reflect the number of oscillation cycles.

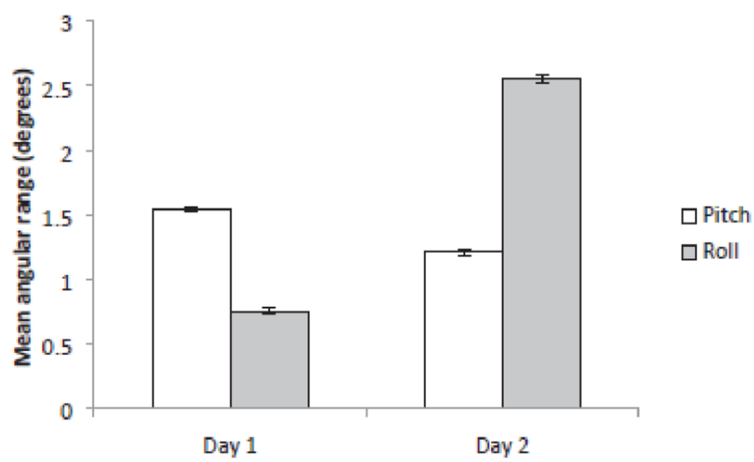

Fig. 4. Angular ship motion (mean range of oscillation cycles, in degrees), illustrating the statistically significant interaction between motion direction (Pitch vs. Roll), and testing days (Day 1 vs. Day 2). Error bars represent the 95% confidence interval of the mean.

Data on the motion of the ship are summarized in Fig. 4. The main effect of days was significant, $F(1,21{,}987)=3278.34$, $p < .001$, partial $\eta 2=0.13$, reflecting the increase in overall ship motion between June 18 (sea state=2.5) and June 25 (sea state=4.0). The main effect of motion was significant, $F(1,21{,}987)=451.39$, $p < .001$, partial $\eta 2=0.02$, with greater overall motion in roll than in pitch. In addition, the Day×Motion interaction was significant, $F(1,21{,}987)=6956.11$, $p < .001$, partial $\eta 2=0.24$, showing greater pitch than roll on Day 1 (June 18) and greater roll than pitch on Day 2 (June 25). As can be seen from the effect sizes, the statistically significant interaction accounted for the majority of the variance.

Mean judgments

The judgment data are summarized in Fig. 5. For each Ship Motion condition, we calculated means for the two judgments of the fore-aft path, and for the two judgments in the athwart path. We conducted a 2×2 repeated measures ANOVAs on these values with factors Ship Motion (Day 1: Pitch > Roll vs. Day 2: Roll > Pitch) and Walking Direction (Fore-aft vs. Athwart). To account for our use of a within-participants design, for statistically significant effects we estimated effect size using the F-value and its degrees of freedom (Lakens, 2013; Eq. (13)). Similarly, we computed effect sizes for post-hoc t-tests using Cohen's d_z (Lakens, 2013; Eq. (7)). The ANOVA

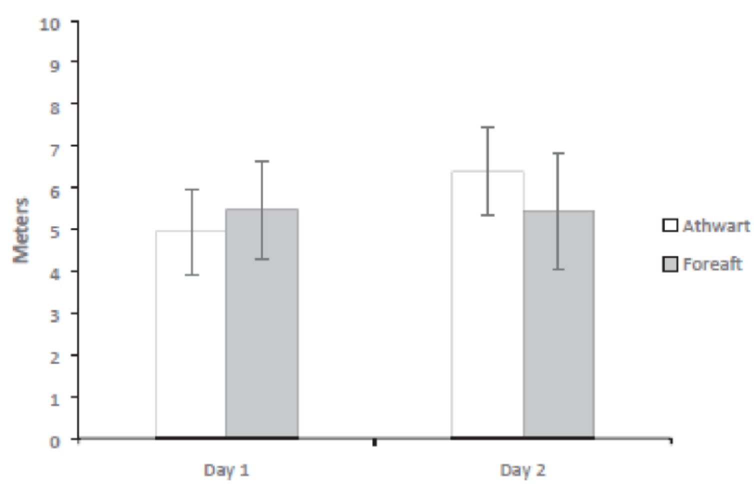

Fig. 5. Mean judgments of walking ability along the fore-aft and athwart paths as a function of ship motion (pitch > roll vs. roll > pitch). Error bars represent the 95% confidence interval of the mean.

revealed that only the Day×Direction interaction was significant, $F(12)=7.87$, $p=.016$, partial $\eta2=0.40$. When pitch > roll (Day 1), participants judged that they could walk further along the fore-aft path than along the athwart path, $t(12)=2.56$, $p=.04$, $dz=0.71$ (see Lakens, 2013). When roll > pitch (Day 2), participants judged that they could walk further along the athwart path than along the fore-aft path, $t(12)=2.26$, $p=.04$, $dz=0.63$. Five participants gave the maximum judgment (890 cm) for each judgment in each direction; that is, they exhibited a ceiling effect.

Walking performance

For performance trials, we took the mean of the six trials for the fore-aft path, and for the athwart path. We conducted 2×2 repeated measures ANOVAs with factors Days (Day 1 vs. Day 2) and Direction (fore-aft vs. athwart paths). The data are summarized in Fig. 6. The ANOVA revealed no significant effects. Despite this outcome, for comparison with Walter et al. (2017), we conducted planned comparisons of effects of walking direction on each testing day. For walking performance on Day 1, the effect of direction was not significant, $t(12)=0.01$, $p > .05$. For Day 2, performance was better (i.e., participants walked farther) when walking along the athwart path than when walking along the fore-aft path, $t(12)=2.49$, $p=.03$.

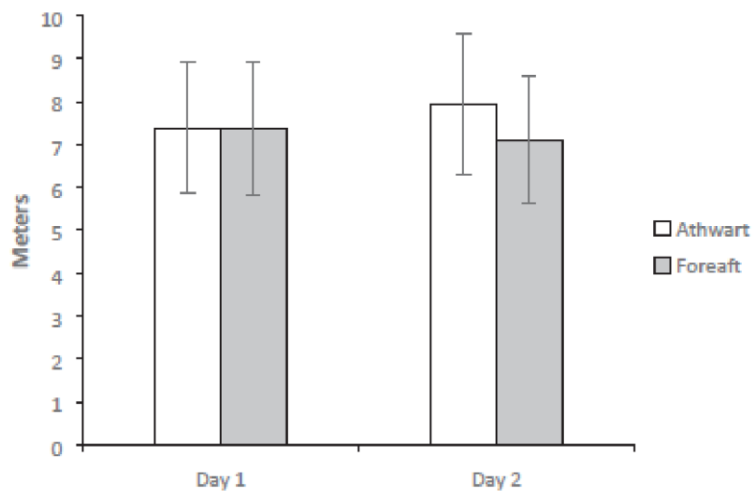

Fig. 6. Performance (mean walked distance) along the fore-aft and athwart paths as a function of ship motion (Day 1: pitch > roll; Day 2: roll > pitch). Error bars represent the 95% confidence interval of the mean.

Judgment accuracy

The data are summarized in Fig. 7. To evaluate the accuracy of judgments, we expressed judgments as a proportion of actual walking performance (judgment mean/performance mean). As can be seen in Fig. 8, on Day 1 the 95% confidence intervals included 1.0 for both walking directions. By contrast, on Day 2, the 95% confidence intervals did not include 1.0, for either walking direction. However, the figure also reveals that the two days differed in the size of the confidence intervals, due to the fact that the standard error of judgment/performance ratios on Day 1 was 2–4 times greater than the standard errors on Day 2.

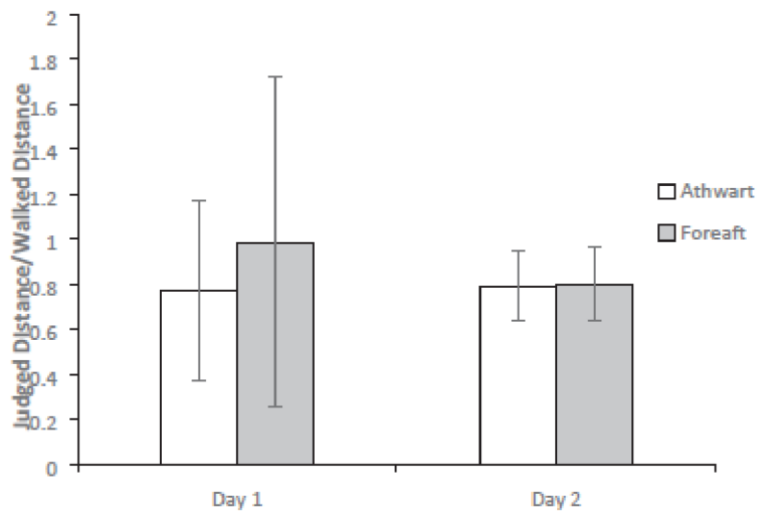

Fig. 7. Mean accuracy of walking judgments (judgment/performance) for the fore-aft and athwart paths as a function of ship motion (Day 1: pitch > roll; Day 2: roll > pitch). Error bars represent the 95% confidence interval of the mean.

To determine whether accuracy varied as a function of conditions, we compared these proportions using a 2×2 ANOVA with factors Ship Motion (pitch > roll vs. roll > pitch) and Direction (fore-aft vs. athwart paths). The ANOVA yielded no significant effects. That is, we found no evidence that judgment accuracy differed as a function of days, or as a function of walking direction.

Discussion

On a ship at sea, we asked experienced maritime crewmembers to judge how far they could walk while remaining within the boundaries of marked paths. One path paralleled the ship's long (fore-aft) axis, while another paralleled the ship's short (athwart) axis. Walking in the two directions was differentially constrained by variations in the relative magnitude of angular ship motion in pitch and roll, created by a combination of ship architecture and sailing conditions. Judgments of walking ability differed as a function of walking direction (i.e., along the fore-aft and athwart paths), and the direction of this difference depend on sailing conditions. Consistent with our predictions, when pitch was greater than roll (Day 1), participants judged that they could walk farther along the fore-aft path than along the athwart path, and when roll was greater than pitch (Day 2), participants judged that they could walk farther along the athwart path than along the fore-aft path. That is, building on the results of Walter et al. (2017), we found that perception of affordances for walking on a ship at sea not only reflected patterns of ship motion occurring under typical sailing conditions (Day 2) but also reflected the qualitative reversal in such patterns occurring under atypical sailing conditions (Day 2).

Adaptive perception of differing constraints

It might be that experienced mariners' knowledge of affordances for nautical walking is related to their existing knowledge that the ship is longer than it is wide, and/or to previous experience of typical sailing conditions in which pitch is greater than roll. Alternately, experienced mariners might flexibly and spontaneously exhibit sensitivity to how (both typical and atypical) patterns of ship motion influence their ability to walk on the open deck. If so, then experienced mariners' judgments of affordances for nautical walking should change with changes in relevant parameters of ship motion. In the present study, our primary prediction was that perception of affordances for walking along the fore-aft and athwart paths would be influenced by changes in the relative magnitude of angular ship motion in pitch and roll across sailing conditions. We were fortunate to experience days at sea in which the relative magnitude of ship motion in roll and pitch differed qualitatively (Fig. 4). This occurrence permitted us to ask whether participants were sensitive to changes in affordances for walking that arose from these naturally occurring changes in ship motion and that reversed the typical relative magnitudes of pitch and roll (see Walter et al., 2017). The judgment data make clear that this was so (compare Figs. 5 and 6), confirming our prediction. That is, experienced mariners judged that their direction-specific walking ability varied in relation to actual variations in the relative magnitude of pitch and roll. That perception of affordances for walking on a ship at sea reflected qualitative differences in ship motion occurring under both typical and atypical sailing conditions is the principal result of our study. The results of Walter et al. (2017) indicated that experienced mariners were sensitive to affordances arising from dynamics of the body and the ship. In the present study, our results indicate that experienced mariners were sensitive to the dynamics of those dynamics.

Overall, participants judged that they could walk further when roll > pitch than when pitch > roll (Fig. 5). This was true despite the fact that overall ship motion was greater in the former case than in the latter (Fig. 4). Especially in light of differences in variability of accuracy across such conditions (Fig. 7), this pattern of results is likely an effect of the relative novelty of sailing conditions in which pitch > roll (such as on Day 1). The finding that walking direction always influenced judgments of walking ability suggests that participants detected the nature of influence of ship motion on walking affordances in both ship motion conditions, but that in the less familiar motion condition (pitch > roll) they may have been less able to detect the magnitude of the effect.

On Day 2, roll was greater than pitch, as was the case in the study of Walter et al. (2017). The results on this day of testing directly replicated the effects reported by Walter et al., on a different ship, in a different sea, with different participants. The actual values of the judgments also were similar, as can be seen by comparing the right side of Fig. 5 from the present study with the left side of Fig. 4 from Walter et al. In the Condition×Direction interaction, the effect sizes for the post-hoc t-tests were very similar to those reported by Walter et al. (2017; d_z=0.98), These large effect sizes testify to the profound influence of ship motion on human behavior (especially walking behavior) and are consistent with findings from previous studies. For example, Chen and Stoffregen (2012) evaluated the kinematics of standing body sway when participants stood facing the ship's bow (front), or its port (left side, when facing the bow). With a sample size of only 9, this simple manipulation yielded a statistically significant effect with an effect size of partial $\eta 2$=0.81. In other studies of standing posture at sea, effect sizes (partial $\eta 2$) up to and exceeding 0.90 have been observed (e.g., Stoffregen et al., 2013; Varlet et al., 2014, 2015).

At sea, oscillatory motion of ships has powerful effects upon human performance. As noted by Stevens and Parsons (2002, p. 29; cf. Wertheim, 1998), "ship motions limit a crews' ability to perform essential command, control, and communications functions, navigation tasks, maintenance responsibilities, and even the preparation of food". For crew members who are standing or walking, effects of ship motion have been most closely studied in the context of motion-induced interruptions, or

MII (Crossland et al., 2007). Analyses of MII have focused exclusively on the physical dynamics of ship motion in relation to a hypothetical "tipping point" for the body (Graham, 1990). In analyses of human movement at sea, little attention has been paid to psychological characteristics of crew members, including skill-related aspects of performance, or crew members' knowledge of their ability to stand and walk under different conditions. In the present study, we investigated crew members' knowledge of their walking abilities as a function of natural variations in the angular motion of a ship at sea.

Across walking directions and across days the static properties of the deck were constant, including its material substance, its topography, the way it reflected light, and so on. Only the dynamic properties of the deck varied, as a function of how the ship moved. Thus, the differences in judgments across variations in ship motion provide evidence that the perception of dynamically defined affordances was itself dynamic. These results provide empirical support for the general hypothesis that the perception of affordances is an emergent phenomenon–occurring online and in real time and reflecting changes in the dynamic fit between animal and environment over multiple time scales (cf. Adolph, Robinson, Young, & Gill-Alvarez, 2008; Mark et al., 1990).

On each testing day, we were able to control the order of presentation of the fore-aft and athwart conditions. By contrast, across testing days, we were not able to control the order of presentation of the ship motion conditions (roll > pitch vs. pitch > roll). This, this aspect of our design was unbalanced. Logically, the results might be influenced by the fact that all participants were tested first when pitch > roll, and second when roll > pitch. For example, it might be the case that the experience of judging walking ability when pitch > roll might influence later judgments of walking ability when roll > pitch. While we acknowledge this logical possibility, we regard the possibility of such an influence on our results as highly unlikely. The principal reason is the fact that the two ship motion conditions were separated by a full week (see Section 2.1). During that intervening week, sailing conditions varied naturally, and participants (along with everyone else onboard) were obliged to perceive and control all of their movements relative to these natural variations in ship motion. If it is admitted that mariners in fact perceived their walking ability and used that knowledge to control walking each day, then it seems extremely unlikely that the brief experience of providing explicit judgments of walking ability on Day 1 would have retained any power to influence judgments made a week later.

Time scales

In our study, pitch and roll motion of the ship occurred over relatively short time scales (i.e., seconds, or individual footfalls), while quantitative and qualitative changes in the relative magnitude of pitch and roll occurred over longer time scales (i.e., days). It might appear, then, that participants calibrated their perception to conform to a particular (relatively stable) set of sea conditions that characterized an entire day. Our results are consistent with this view, but they do not mandate it. Our results also are consistent with at least one alternative view. Variations in the relative magnitude of pitch and roll can occur across days; however, such variations also occur over shorter time scales. One such time scale is minutes or even seconds, as often occurs when a ship turns, changing its heading relative to the prevailing waves and swell. When a ship turns, changes in the relative affordances for walking along the fore aft versus athwart paths would occur over time scales similar to those relating to both judgments and performance. Our results are consistent with the possibility that perception of changing affordances for walking fore-aft versus athwart, arising from changes in the relative magnitude of pitch and roll, may have occurred over time scales equivalent to those over which the underlying conditions, themselves, were changing (cf., Newell, Liu, & Mayer-Kress, 2001; O'Neal et al., 2018). This hypothesis could be evaluated by testing across controlled changes in a ship's heading.

Judgment accuracy

We evaluated the accuracy of affordance judgments by expressing judgments as a proportion of actual performance (judged/actual). On each testing day, the accuracy of affordance judgments did not differ between the fore-aft and athwart paths (Fig. 7). That is, variations in the relative magnitude of roll and pitch affected judgments of walking ability, but did not affect participants' sensitivity to their walking ability. This result replicates and extends a finding reported by Walter et al. (2017).

When pitch > roll, judgment accuracy was more variable than when roll > pitch (Fig. 7). There are a number of possible explanations for differences between judged and actual abilities (see Wagman, Bai, & Smith, 2016). However, given the relative paucity of situations under which pitch exceeds roll, in our case the most likely explanation is that participants were insufficiently attuned to stimulation patterns that were informative about walking ability under such (unusual) conditions. Consistent with such a proposal, research has shown that, when action capabilities have been altered, repeated experience perceiving affordances for a given behavior is sufficient for improvements in accuracy of such perception (Higuchi et al., 2004; Mark et al., 1990). We predict that such a process underlies perception of affordances at sea. That is, we predict that, given additional judgment trials without practice or feedback, the accuracy of participant's judgments of walking affordances when pitch > roll would become less variable.

Conclusion

Sea travel predates all other forms of non-ambulatory translation. The domestication of horses occurred approximately 6000 years ago (Anthony, 2007), and terrestrial vehicles and aviation are more recent. By contrast, seafaring may extend back 1,000,000 years (Bednarik, 1999). Thus, people (and other animals) have been adjusting perception and action in relation to ship motion for far longer than other modes of transport. Unlike the present day, when we can fly over water, for many centuries, seafaring was the only way to cross oceans. Consequently, many millions of people had no choice but to "get their sea legs".

On a ship at sea, we asked participants (experienced mariners) to judge their ability to walk along marked paths that were parallel to the long and short axes of the ship. Judgments were made under different sailing conditions that qualitatively altered the relative magnitude of the ship's angular motion in pitch and roll. Judgments of walking ability in different directions reflected this qualitative shift in the relative magnitude of pitch and roll, confirming that (in experienced mariners) judgments were dynamic, and were affected by actual variations in ship motion. We interpret these results as demonstrating a new type of flexibility and adaptability in the perception of affordances.

CHAPTER IV: Sensitivity to changes in dynamic affordances for walking on land, and at sea

Introduction

Affordances are possibilities for action that exist for a given animal in a given environment (Gibson, 1979, 1987; Stoffregen, 2003). For example, affordances for locomotion emerge from relations between properties of an animal and properties of the environment that allow for movement from place to place (e.g., Lee et al., 1984; Plumert et al., 2011). One type of locomotion is walking.

Walking necessarily includes lateral oscillations of the body as weight shifts between the feet. These oscillations are not static states of the body. Rather, they are movements. These lateral oscillations can influence relations between properties of the animal and the environment, that is, they can influence affordances for walking. Franchak et al. (2012) asked adults to judge their ability to walk through doorways that varied in height, or in width. After making judgments, participants walked through the doorways. Comparison of judgments and actual walking revealed that for variations in doorway width judgments were not strongly related to the static body of shoulder width but, rather, to the dynamic property of lateral oscillations in walking; what the authors referred to as the width of the body in motion. Walking along a narrow path (for example, a gap between buildings, or along a balance beam) will be constrained by the walker's ability to control lateral oscillations, so as to avoid bumping into walls (when walking between buildings) or falling off the path (when walking on the beam). The greater the person's ability to control lateral oscillations, the farther they can walk along a narrow path.

How far can you walk?

Traditionally, effects of lateral oscillations on walking have been interpreted with respect to step width (e.g., Maki, 1997; Wollesen & Voelcker-Rehage, 2019). In the present study, we considered effects of lateral oscillations on affordances for walking a maximum distance along a narrow path (Walter et al., 2017; 2019A). The developmental literature comprises extensive research on affordances for walking (e.g., Adolph, 1995; Franchak & Adolph, 2012). In adults, research has focused mainly upon affordances for walking through doorways (e.g., Franchak, et al., 2012; Higuchi et al., 2011; Warren & Whang, 1987). We know of no existing research on perception of affordances relating to how far a person can walk along a narrow path in a given situation or under given circumstances. There is a considerable empirical literature on step width, but this research typically has addressed clinical issues, in part because control of lateral oscillation rarely is an issue for healthy adults (Maki, 1997; Wollensen & Voelcker-Rehage, 2019). However, environmental conditions can challenge the control of lateral oscillations in walking. An example is walking on a ship at sea.

Humans have been going to sea for many thousands of years (Erlandson, 2001). Ocean swells and waves generate oscillatory motion of ships, with motion excursions typically on the order of meters. Ship motion varies with changes in wind, waves, ship speed and heading, among other factors, but is present around the clock, day in and day out, for the duration of a voyage (Wertheim, 1998). This highly complex motion of the ground surface is associated with broad changes in perceptual-motor control. Perhaps best known are changes in gait: The rolling gait of fully adapted mariners often is visible to casual observers (Stevens & Parsons, 2002). Recent research on ships at sea has shown that experienced mariners accurately detect the influence of ship motion on affordances for walking; specifically, how oscillatory ship motion alters the maximum distance that an individual can walk along a narrow path. In previous studies, independent variables were properties of ship motion (Walter et al., 2017; 2019A). In the present study, we asked how affordances for walking along a narrow path might be influenced by changes in properties of the body.

Added mass and affordances for walking

Of greatest relevance to the present study is the fact that changes in the body's mass (and mass distribution) tend to influence available actions (e.g. Adolph & Aviolo, 2000). For example, Chow et al. (2005) loaded adolescent girls (age 10-15 years) with up to 15% of their body weight in backpacks. Weights exceeding 10% of body weight disrupted alternating gait patterns and changed the placement of footfalls. In adults, added mass also can change perception of affordances. Regia-Corte and Wagman (2008) asked participants to wear a backpack apparatus to which masses were attached in one of three configurations—high-mass, low-mass, or no-mass. In each condition, participants adjusted the angle of inclination of a surface until they felt that it was just barely possible for them to stand on that surface. Perception of affordances for standing on the inclined surface reflected the changes in center of mass brought on by the weighted backpack apparatus, as shown by the fact that the perceptual boundary occurred at a smaller angle of inclination in the high-mass condition than in either the low-mass condition or the no-mass condition.

Learning about changed affordances

In the studies of Walter et al. (2017; 2019A), participants were experienced mariners who were fully adapted to ship motion. The impressive sensitivity of this population of participants demonstrated in the studies of Walter et al., raises questions about how people learn about changes in affordances for walkable distance over both short and long time scales. In a classic study, Mark (1987) asked standing participants to judge their maximum sitting height, that is, the highest chair on which they could sit. A key aspect of Mark's design was that participants made a series of judgments. In one condition, participants made these judgments while wearing 10 cm blocks on their feet. These blocks increased actual maximum sitting height. In the initial judgments while wearing the blocks, participants' responses reflected their sitting ability without the blocks. That is, initial judgments were underestimates. However, across the series of judgment trials, judgments gradually improved. By approximately the eighth judgment trial (out of a total of 12), the mean judgment (across participants) accurately reflected actual (increased) sitting ability while wearing the blocks. This gradual improvement in judgments was remarkable because participants received no feedback about the accuracy of their judgments, and were not permitted to practice the act of sitting while wearing the blocks. Between judgments, participants were permitted to walk around the laboratory, but Mark et al. (1990) found that this experience was not necessary for such improvements to occur. Improvements over trials occurred even when participants stood still throughout Experiment 2, but walking between trials served to reduce variability in judgments. Mark et al. (1990; cf. Stoffregen, Yang, & Bardy, 2005; Yu et al., 2011) showed that exploratory movement of the body (e.g., postural sway) was both necessary and sufficient for gradual retuning of judgments.

Learning about affordances for walking

In the present study, we asked whether this spontaneous learning of affordances (i.e., without feedback about judgment accuracy) would occur in the context of changes in affordances for walking defined dynamically (in terms of the effect of mass distribution of the body on lateral oscillations) rather than geometrically (in terms of the effect of between leg length on stepping height).

The blocks used by Mark (1987) and Mark et al. (1990) raised the ankles above the ground. This change altered the multisensory consequences of body sway. In particular, standing on blocks influenced relations between ankle rotation and the corresponding changes in optic flow. Similarly, adding weight to the torso would also affect relations between self-generated movement and corresponding changes in optic flow. Therefore, body sway could be expected to generate information about the consequences of added torso weight for stabilization of the body. By contrast, it was less clear whether weight added at the ankles would alter sway in ways that generated relevant information. To ensure that such information would be available, before beginning the sequence of judgment trials, we provided participants with a form of experience moving (but not walking) while wearing the weights. Following the logic of Mark, they were not permitted to practice the act that they would be judging, that is they were not permitted to walk. Rather, to experience how the weights influenced movement in general, participants stepped in place. To ensure that this experience could not provide direct information relating to visible distance, participants did so while blindfolded.

The walking task developed by Walter et al. (2017; 2019A) focused on dynamically defined affordances for walking, with independent variables in properties of the environment (aspects of ship motion). In Experiment 3, we used a similar walking task, with independent variables in properties of the body; specifically, weights added to the body that were expected to influence walking ability (cf. Adolph & Aviolo, 2000; Mark, 1987; Mark et al., 1990). Our primary aim was to determine whether participants were prospectively sensitive to how added weight influenced their walking ability. Our secondary aim was to determine whether participants' sensitivity to weight-related changes in walking ability exhibited spontaneous learning of the kind reported by Mark (1987; Mark et al., 1990). We expected that weight conditions would influence walkable distance. Across the series of judgment trials, we predicted that judgments would be both stable and accurate in the control (no added weight) condition. In conditions with added weight, however, we predicted that initial judgments would initially be less accurate, but would come to reflect the changed walking ability over the series of judgment trials, consistent with effects reported by Mark (1987; Mark et al., 1990). In Experiment 4, we used a similar methodology on a ship at sea: Our aim was to assess sensitivity to the simultaneous influence of dynamic properties of the body (added weight) and dynamic properties of the environment (ship motion).

Experiment 3

In Experiment 3, our principal purposes were to 1) evaluate effects of added weight on participants' ability to walk within a narrow path, and 2) to investigate whether actual differences in performance were reflected in prior judgments of walking ability. We predicted that added weight would reduce the distance that participants could walk within the narrow path. We also predicted that effects of the weights would be reflected in judgments of maximum walkable distance.

Previous research has focused on mass added to the torso, often with the deliberate intention of simulating school backpacks (e.g., Chow et al., 2005; Cottalorda et al., 2003; Hong & Bruggeman, 2000; Li et al., 2003). Mass can also be added to the lower extremities, for example, when wearing heavy ski boots, medical walking boots, or fitness weights on the ankles. We reasoned that, in the context of our path-following task, a greater challenge to lateral gait would arise from weight added to the ankles than to the torso but that there would be greater changes to perceptual information during postural sway from weights added to the torso than to the ankles. For this reason, in Experiment 3 we separately evaluated effects on perception and performance of weights added at the upper torso, and at the ankles.

Our method was based upon prior studies of both perception and performance on land (e.g., Mark, 1987; Mark et al., 1990), and at sea (Walter et al., 2017; 2019A). However, we modified the method to take into account the nature of our manipulations in the present study. Given that the addition of weights was sudden and discrete, such that participants had little or no prior exposure to gait while wearing the weights (cf. Chow et al., 2005; Garciaguirre, Adolf, & Shrout, 2007), we expected that performance (actual walking ability, in terms of distance walked and the speed of walking) might change across performance trials. In addition, following previous studies (e.g., Mark, 1987; Mark et al., 1990; Stoffregen, Yang, & Bardy, 2005), we expected that the accuracy of judgments might change over the course of a series of judgments. For this reason, we asked participants to make a series of eight judgments before engaging in any actual walking. We predicted that judgments would change, over trials, in conditions with added weight, but that they would not change in the baseline condition (no added weight). Following Mark et al. (1990), we evaluated these predictions in terms of the slope of the line across the series of eight judgments for each condition.

In both Experiment 3 and 4, to account for our use of a within-participants design, for statistically significant effects we estimated effect size using the *F*-value and its degrees of freedom (Lakens, 2013; Eq. 13). Similarly, we computed effect sizes for post-hoc *t*-tests using Cohen's d_z (Lakens, 2013; Eq. 7).

Method

Participants

Our sample comprised 14 individuals (5 men and 9 women), ranging in age from 18 to 76 years (mean = 39.21 years), in height from 1.44 to 1.81 m (mean = 1.65 m) and in weight from 49.90 kg to 103.41 kg (mean = 70.18 kg). We selected this age range of participants in Experiment 3 to match those of the crewmembers on the ship who would serve as participants in Experiment 4 (e.g., Mayo et al., 2011; Walter et al., 2017). As part of the consent process, participants indicated that they suffered from no history of balance disorders, vestibular dysfunction, seizures, or dizziness. The experimental protocol was approved in advance by the University of Minnesota IRB.

To ensure a large enough sample size to provide sufficient power reliably to exclude false rejection of the null hypothesis, we tested power (1-β) with the G*Power program (Faul, Erdfelder, Land, & Buchner, 2007), using the *a priori* option and the effect size (.81) for affordance judgments from Walter et al. (2017; *n* = 16). Power analysis revealed a test power of .967 and suggested that a sample size of *n* = 14 would be sufficient to achieve the desired effect size of 0.81.

Table 3 – Experiment 3
Participant Characteristics (n = 14)

Participant Number	Sex	Age	Height (cm)	Weight (kg)	BMI
1	M	76	171.5	87.09	26.3
2	M	31	176.4	79.38	25.5
3	F	26	164.15	49.9	18.5
4	F	34	159.25	65.77	25.9
5	M	22	172.73	79.37	26.6
6	F	23	144.55	54.43	26.0
7	F	66	161.7	57.61	22.0
8	M	29	173.95	100.7	33.3
9	F	37	154.35	49.9	20.9
10	M	56	181.3	103.41	31.5
11	F	18	161.7	54.43	20.3
12	F	27	159.25	53.07	20.9
13	F	42	162.93	65.77	24.8
14	F	62	161.7	81.65	31.2

Setting and apparatus

The study was conducted on a basketball court in Williams Arena at the University of Minnesota. In some conditions, athletic weights were applied to the body.

We used a weighted vest (j/fit, Vancouver WA), in which 9.1 kg were distributed symmetrically left to right, and front to back. We also used two soft, wrap-around athletic weights (Synergee, Thunder Bay Ont) each 4.55 kg, that could be secured at the ankle using Velcro.

Procedure

We created a pathway using matte tape on the court, parallel to the sidelines. Following previous studies (Walter et al., 2017; 2019A), the pathway was 8.9 m long × 0.3 m wide. We used a within-participants design. Participants were tested with their shoes on (at sea, in Experiment 4, this was required). In the No Weight condition, the participant wore no weights attached to the body. In the Torso weight condition, the participant wore the weighted vest. In the Ankle weight condition, the participant wore one 4.55 kg weight attached at each ankle.

Stepping in place

Stepping in place was conducted with the participant standing at the beginning at one end of the path, with their heels on a marked line. A blindfold (an opaque elastic head band) was applied, after which (in the Torso weight and Ankle weight conditions) weights were attached. With the blindfold in place, the participant engaged in stepping in place, that is, sequentially raising

Fig. 1. A participant stepping in place while blindfolded.

each foot off the ground and returning it to its original position (Fig 1). This took place in all conditions, even in the No Weight condition. Five step cycles were executed (i.e., the right and left feet each were raised 5 times for a total of 10 steps). After stepping in place, the Experimenters assisted the participant in returning their feet to the starting position. Then, the blindfold was removed.

Judgment task

The participant was asked to look at the designated path and estimate “if you were walking comfortably, how far do you think you could walk along this path without stepping on or over the lines?” To report estimated distance, the participant instructed an experimenter where to place a marker (a 0.25 m length of a wooden 4 × 4) along the path. At the beginning of the trial, the experimenter stood near the participant, facing them, and slowly walked backward along the path until instructed to stop by the participant. Each participant gave eight judgments for each condition (No weight, Torso weight, Ankle weight), for a total of 24 judgments. Across participants, we counterbalanced the order in which the three conditions were presented. We repeated the six possible condition orders in a fixed sequence across successive participants.

Performance (walking) task

After completing the judgment task, participants were asked to walk comfortably along the path: “Please do not look at your feet. Keep your eyes on the end of the path and walk so as to avoid stepping on the lines.” For each condition, the participant completed a total of 12 trials, comprising six laps (out and back). Stepping on or over the lines with any part of either foot was classified as a “fault” and the walked distance was recorded from the spot of the fault. For each trial, the participant indicated that they were ready, after which the experimenter gave a "go" signal and started a handheld stopwatch. Each of three experimenters watched for faults, with one experimenter on each side, walking behind so as to be able to monitor footfalls while remaining outside the participant's field of view, while one experimenter remained at the starting point. The stopwatch was stopped when the participant crossed the end line or when a fault was verbally indicated, and the duration of the trial was recorded.

Data analysis

Our analysis was modeled after that of Mark et al. (1990). Mark et al., did not directly investigate whether their principal manipulation (the wearing of 10 cm blocks on the feet) influenced judgments, relative to a control condition in which the manipulation was absent (the no block condition). In each condition, actual maximum sitting ability did not change from trial to trial, such that it made sense for Mark et al. to focus exclusively on the accuracy of judgments, which they operationalized as the ratio of judged to actual maximum sitting height. By contrast, in our study actual walking ability could vary from trial to trial (cf. Adolph, 1995), especially in Experiment 3 (due to dynamic variation in ship motion) and might also change systematically across actual walking trials (i.e., with practice).

For these reasons, in the present study we did not focus on judgment accuracy. Rather, we focused on whether and how the weight manipulations influenced perceived and actual walking ability (with separate ANOVA on means for judgments and for performance) and on whether there were changes across the sequence of judgment trials.

Investigating whether the weight manipulations affected actual walking ability (performance), and whether any changes in walking ability were reflected in changes in mean judgments required that we use within-participants design. Consequently, there was an issue of possible order effects in the presentation of the three experimental conditions. Following Mark et al. (1990), we evaluated effects of our manipulations in terms of main effects in analysis of variance (ANOVA). For each condition, we calculated means for the eight judgments. We conducted a 3 × 6 ANOVA on these values with factors Condition (No Weight, Torso weight, Ankle weight) and Condition Order (1-6). To account for our use of a within-participants design, for statistically significant effects we estimated effect size using the *F*-value and its degrees of freedom (Lakens, 2013; Eq. 13). Similarly, we computed effect sizes for post-hoc *t*-tests using Cohen's d_z (Lakens, 2013; Eq. 7).

Results

Mean judgments

Collapsed across trials, the judgment data are summarized in Fig 2. The main effect of Conditions was significant, $F(2,16) = 24.20$, $p < .001$, partial $\eta^2 = 0.75$. The main effect of Condition Order, and the Conditions × Condition

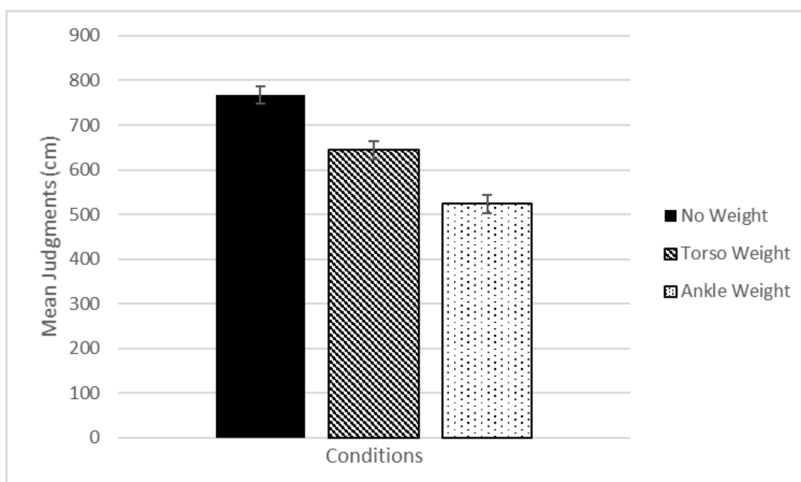

Fig. 2. Mean judgments, across participants and judgment trials, of walkable distance. The error bars represent the standard error of the mean.

Order interaction were not significant. None of the participants gave the maximum judgment (890 cm) for each judgment in every condition; that is, no participant exhibited a ceiling effect.

Changes across judgment trials

The data are presented in Fig 3. Following Mark et al. (1990), we asked whether judged walkable distance changed over the sequence of judgment trials. For each condition, we performed linear regression of judgments across trials. For the No weight condition, linear regression yielded a slope of 3.79, which did not differ from 0, $r^2 = 0.26$, $p = .19$. For the Torso weight condition, the slope, 14.76, was greater than 0, $r^2 = 0.96$, $p < .001$. Similarly, for the Ankle weight condition, the slope, 12.02, was greater than 0, $r^2 = 0.54$, $p < .05$.

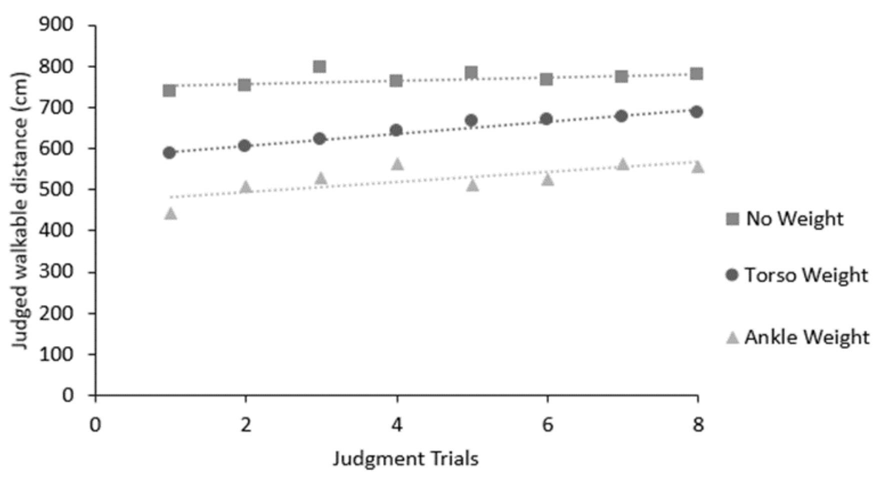

Fig. 3. Mean judgments of walkable distance (across participants) as a function of conditions, and judgment trials.

Walking performance

Distance

The data are summarized in Fig 4. In analyzing the performance trials, we took the mean of the 12 trials for each condition. Using these means, we conducted a 3 × 6 repeated measures ANOVA with factors Conditions (No weight, Torso weight, Ankle weight) and Condition Order (1-6). The main effect of Conditions was significant, $F(2,16) = 4.64$, $p = .026$, partial $\eta^2 = 0.367$. The main effect of Condition Order, and the Conditions × Condition Order interaction were not significant.

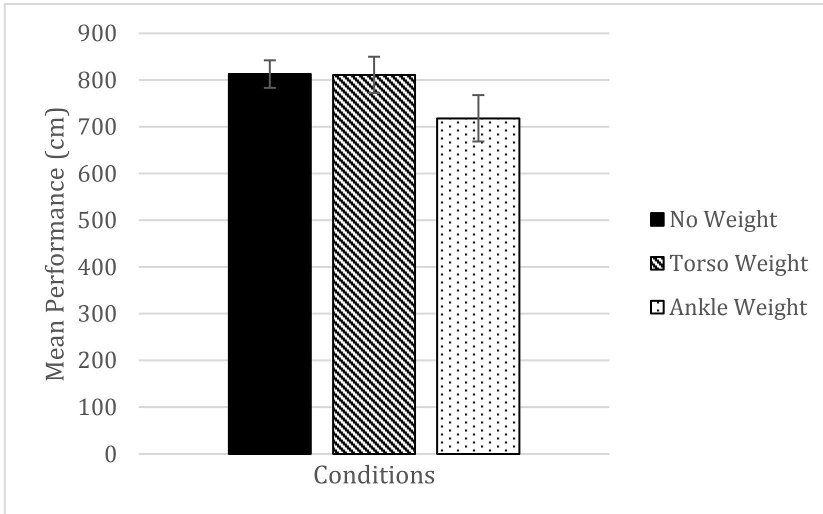

Fig. 4. Actual walked distance (mean across participants) as a function of conditions. The error bars represent the standard error of the mean.

Speed

Using data on distance walked and duration, we computed walking speed for each performance trial. These data are summarized in Fig 5. In analyzing walking speed, we took the mean of the 12

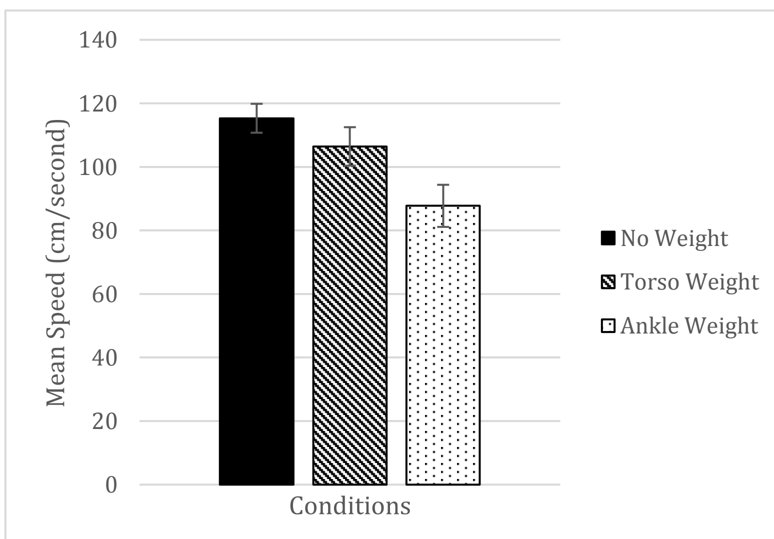

Fig. 5. Walking speed (mean across participants) as a function of conditions. The error bars represent the standard error of the mean.

trials for each condition. Using these means, we conducted a 3 × 6 repeated measures ANOVA with factors Conditions (No weight, Torso weight, Ankle weight) and Condition Order (1-6). The main effect of Conditions was significant, $F(2,16) = 17.90$, $p < .001$, partial $\eta^2 = 0.691$. The main effect of Condition Order, and the Conditions × Condition Order interaction were not significant.

Discussion

In Experiment 3, standing participants made judgments about the distance they could walk along a narrow path. In a within-participants design, each participant made a series of judgments while wearing weights on their ankles, on their upper torso, and in a control condition with no added weight. We predicted that added weight would reduce actual walking ability; that is, we predicted that added weight would reduce both the distance that participants could walk within the narrow lane, and the speed at which they walked. We also predicted that effects of the weights would be reflected prospectively in judgments of maximum walkable distance. Finally, following Mark (1987; Mark et al., 1990), we predicted that, in the added weight conditions, initial judgments would be relatively inaccurate, and that accuracy would improve across the series of judgments, despite the absence of walking practice, or judgment feedback. Each of these predictions was confirmed.

Experiment 4

Motion of a ship at sea tends to alter walking gait, a phenomenon that has been reported anecdotally for thousands of years (Stevens & Parsons, 2002; Wertheim, 1998).

Recent research has begun to document some of these alterations. Oscillatory ship motion changes the sequential timing of footfalls in gait (Haaland et al., 2015), as well as the number of steps taken (Chang et al., 2015). Walter et al. (2017; 2019A) showed that oscillatory ship motion altered the ability of experienced maritime crewmembers to walk along narrow paths laid out on the open deck, and that these changes were reflected in prospective judgments of walking ability. In these studies, affordances for walking were influenced by dynamic properties of ship motion; principally, the multi-axis, aperiodic oscillations of the ship under the influence of wind and waves.

In Experiment 3, we found that participants were prospectively sensitive to changes in walking affordances brought about by changes in the body (added weight) that influenced dynamically the control of walking. In Experiment 4, we asked whether this sensitivity would be preserved when dynamic changes in the body (the wearing of added weights) were coupled with dynamic changes in the environment that also influence walking ability; namely, the aperiodic motion of a ship at sea. In previous studies, it has been shown that subtle, task-related properties of body sway (e.g., Chen & Stoffregen, 2012) and interpersonal coordination (Varlet et al., 2015) can be robust to oscillatory ship motion. In Experiment 4, we asked whether this might also be true of prospective judgments of affordances for walking.

In Experiment 4, our participants were working crewmembers. In consideration of their limited availability, we included only one of the weight conditions that had been used in Experiment 3 (thereby shortening the experimental protocol by approximately one third). In Experiment 3, the largest difference between conditions was between the No Weight and Ankle Weight conditions (Fig 2). Accordingly, in Experiment 4 we used these two conditions only. Except as indicated below, in all other respects, the procedure in Experiment 4 was identical to that of Experiment 3.

Method

Participants

Our sample comprised 9 individuals (8 men and 1 women), ranging in age from 22 to 62 years (mean = 39.78 years), in height from 1.6 to 2.03 m (mean = 1.75 m) and in weight from 49.9 to 108.8 kg (mean = 81.13 kg), and with 1-37 years (mean = 15.1 years) experience working at sea. Participants were working crew members who volunteered (with the Captain's permission), taking time off from their regular duties. None of these individuals had participated in our earlier studies (Walter et al., 2017; 2019A). As part of the consent process, participants indicated that they suffered from no history of balance disorders, vestibular dysfunction, seizures, or dizziness. The experimental protocol was approved in advance by the University of Minnesota IRB, and written informed consent was obtained from each participant. At sea, the number of participants is limited by a number of factors. Testing can be conducted only under appropriate weather conditions; neither calm (such that ship motion would be absent), nor so rough as to prohibit safe walking. For Experiment 4, only one day at sea was suitable for testing. On that day, the number of participants was limited to individuals who choose to volunteer. For these reasons, we computed post-hoc power, which is reported below.

Table 4 – Experiment 4

Participant Characteristics (n = 9)

Participant Number	Sex	Age	Height (cm)	Weight (kg)	BMI	Years at Sea
1	M	48	180	90.7	28.0	28
2	M	37	173	108.8	36.4	6
3	M	47	165	99.8	36.7	6
4	M	23	203	83.9	20.4	5
5	M	62	175	79.4	25.9	37
6	M	53	175	77.1	25.2	28
7	M	38	175	79.4	25.9	21
8	F	22	160	49.9	19.5	4
9	M	28	168	61.2	21.7	1

Setting

The study was conducted during a 5-day cruise aboard the R/V Sally Ride, from San Diego CA to Newport OR. The ship was 86.26 m long with a 15.24 m beam. It displaced 3043 tons and cruised at 10-12 knots.

Procedure

The ship departed San Diego CA on June 26, 2018 and arrived in Newport OR on June 30, 2018. The data were collected on June 29. Data were collected during full daylight, between 9:00 and 17:00.

Testing was conducted on the rear deck of the ship (the fantail), which was free from clutter (Fig. 6). One pathway (8.9 m long × 0.2 m wide) was created using

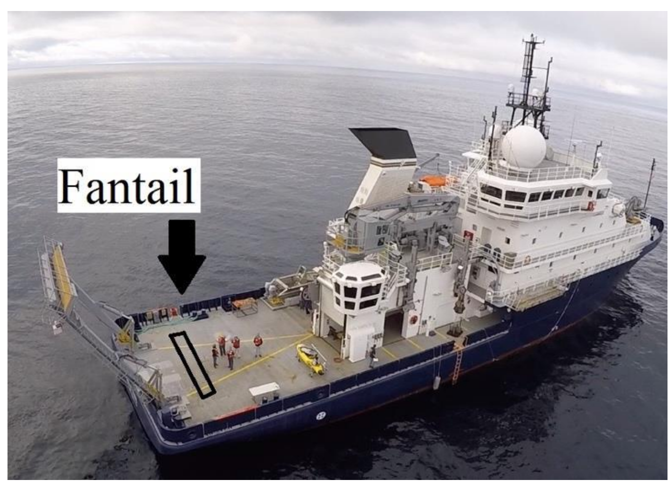

Fig. 6. Aerial view of R/V Sally Ride, showing the open rear deck, or *fantail*. The black rectangle indicates the pathway used in Experiment 2. Note: In the photograph, the pathway is not drawn to scale.

clearly visible gaffer tape. On the first day at sea, a preliminary assessment suggested that walking was not strongly constrained when the path width was 30 cm. For this reason, in Experiment 4, path width was set at 20 cm. The pathway was parallel to the ship's short (athwart) axis. Judgment data were collected with the participant standing at one end of the pathway. At this starting location, participants stood with their feet on the taped lines. The purpose was to standardize foot position to reduce variation in the walking distance. We used a within-participants design, in which each individual participated in both conditions.

Results

During testing, the sea state declined from 7 to 4 on the Beaufort Scale (Beer, 1997). Anecdotally, during the familiarization phase participants' gait appeared to be natural and comfortable. By contrast, during the walking performance trials (i.e., after completing judgments), participants often made visible efforts to maximize their performance, such as waving their arms or shortening their stride. That is, in their actual walking performance they appear to have tried to "walk as far as possible", rather than to "walk comfortably". We did not exclude these trials from our analysis.

Mean judgments

One participant gave the maximum judgment (890 cm) on all trials in both conditions and, for this reason, was deleted from our analysis, leaving a sample size of 9. For each condition, we calculated means for the eight judgments. We conducted a 2 × 2 repeated measures ANOVAs on these values with factors Conditions (No weight vs.

Ankle weight) and Condition Order (No weight – Ankle weight vs. Ankle weight – No weight). The ANOVA revealed that the main effect of Conditions was significant, $F(1,7) = 8.06$, $p = .025$, partial $\eta^2 = 0.54$. The observed power for this effect was 0.684. Judged walkable distance in the No weight condition (mean = 535.23 cm, SE = 48.17 cm) was greater than in the Ankle weight condition (mean = 429.44 cm, SE = 56.59 cm). In addition, the main effect of Condition Order was significant, $F(1,7) = 14.76$, $p = .006$, partial $\eta^2 = 0.68$. Across conditions, mean judgments were greater when the Ankle weight condition was presented first (mean = 671.07 cm, SE = 73.24 cm) than when the No weight condition was presented first (mean = 293.59 cm, SE = 65.51 cm). The Condition × Condition order interaction was not significant.

Changes across judgment trials

The data are summarized in Fig 7. Following Mark et al. (1990), we asked whether judged walkable distance changed over the sequence of judgment trials. For each condition, we used linear regression of judgments across trials. For the No weight condition, linear regression yielded a slope of 21.93, which was significantly greater than 0, $r^2 = 0.85$, $p < .001$. For the Ankle weight condition, the slope, 13.80, did not differ from 0, $r^2 = 0.49$, $p > .05$.

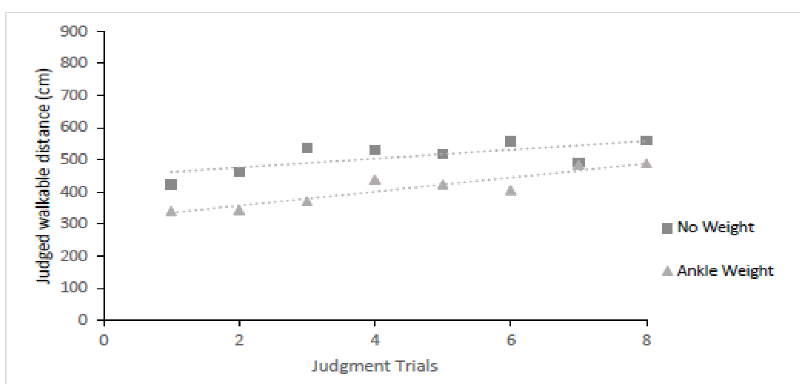

Fig. 7. Experiment 2. Mean judgments of walkable distance (across participants) for each condition as a function of judgment trials.

Walking performance

Distance

We took the mean of the 12 trials for each condition. We conducted a 2 × 2 repeated measures ANOVA with factors Conditions (No Weight vs. Ankle Weight) and Condition Order (No Weight – Ankle Weight vs. Ankle Weight – No Weight). The ANOVA revealed no significant effects.

Speed

We took the mean of the 12 trials for each condition. We conducted a 2 × 2 repeated measures ANOVA with factors Conditions (No Weight vs. Ankle Weight) and Condition Order (No Weight – Ankle Weight vs. Ankle Weight – No Weight). The main effect of Condition was significant, $F(1,7) = 8.62$, $p = .022$, partial $\eta^2 = 0.552$. Speed in the No weight condition (mean = 91.86 cm/s, SE = 10.81 cm/s) was greater than in the Ankle weight condition (mean = 82.20 cm/s, SE = 9.70 cm/s). There were no other significant effects.

Discussion

On a ship at sea, we asked experienced maritime crewmembers to judge how far they could walk while remaining within the boundaries of a marked path with no added weight, or while wearing weights at the ankles. Participants judged that they could walk further with no added weight than when wearing the ankle weights. Over the series of eight judgment trials in each condition, judgments changed in the No Weight condition, more closely reflecting actual walking ability over the course of the eight trials.

Actual distance walked did not differ between the conditions, but participants walked more slowly when wearing the ankle weights than with no weight. In the Torso weight condition, it might be that the weights, while making walking more effortful (due to the overall increase in mass), also functioned to stabilize the body with respect to ship motion. A related effect was reported by Malek and Wagman (2008), who found that wearing a weighted pack on the chest increased the maximum uphill slope on which participants could stand.

The fact that mean judgments were reduced in the Ankle Weight condition suggests that participants accurately detected the influence of added weight on their walking ability. Walter et al. (2017) demonstrated that maritime crewmembers were sensitive to variations in affordances for walking that arose from direction-specific variations in ship motion (walking fore-aft vs. walking athwartship). Walter et al. (2019A) showed that sensitivity to these direction-specific constraints was itself robust across qualitative changes in ship motion (i.e., in the relative magnitude of roll and pitch). These earlier results demonstrate that participants could detect effects of ship motion on their own walking ability. In Experiment 4 of the present study, judgments varied across conditions despite the fact that, between conditions, there was no systematic difference in the motion characteristics of the ship. Thus, the main effect of conditions in our Experiment 4 suggests that participants differentiated the constraints on walking ability imposed by added weight (which changed across conditions) from those simultaneously imposed by ship motion (which did not). The present result thus extends the findings of Walter et al. (2017, 2019A), to the domain of variations in the dynamic properties of the body.

On land, in Experiment 3, judgments in the No weight condition were accurate, and were stable across judgment trials, consistent with Mark (1987), and Mark et al. (1990). At sea, in Experiment 4, the finding that accuracy improved across judgment trials in the No Weight condition suggests that our task was novel for our maritime crewmembers. The lack of change over trials in the Ankle Weight conditions may be due to the heightened variability of judgments in this condition.

General Discussion

In Experiments 3 and 4, we manipulated properties of the animal and of the environment that would tend to influence the distance that could be walked along a narrow path. In Experiment 3, weights affixed to the body (at the torso, or at the ankles) altered participants' judgments of the distance that they could walk within a narrow path. Prior to actual walking, judged maximum walkable distance changed over the course of a series of judgment trials when wearing weights, but did not change when no weight was worn. Overall mean judgments differed between the weight conditions, and reflected actual differences in (subsequent) walking ability.

In Experiment 4, we evaluated the "no weight" and "ankle weight" conditions on a ship at sea, such that affordances for walking along the narrow path were influenced simultaneously by affixed mass and ship motion (oscillation in pitch). Judged maximum walkable distance again differed between conditions, reflecting actual differences in (subsequent) walking. In the "no weight" condition (but not in the "ankle weight" condition), means changed over the course of a series of judgments, suggesting that the task was novel for our participants (experienced maritime crewmembers).

Adaptive perception of differing constraints

In each experiment, weights added to the body reduced actual walking ability, in terms of distance walked and/or walking speed, consistent with previous research (Adolph & Aviolo, 2000; Chow et al., 2005). In addition, in each experiment, added weight reduced prospective judgments of walking ability. Previous studies have demonstrated prospective sensitivity to affordances relating to the width of the body (the shoulders, or the midriff) in walking through apertures (Franchak, van der Zalm, & Adolph, 2010; Warren & Whang, 1987). Our results extended these earlier studies by demonstrating prospective sensitivity to affordances relating to the ability to control lateral placement of the feet in walking.

Learning across judgments

Mark (1987; Mark et al., 1990) required participants to wear 10 cm blocks on their feet, which increased their actual maximum sitting height. While wearing the blocks, initial judgments of maximum sitting height were relatively inaccurate. However, over the series of judgments, accuracy improved. In the present study, we adapted Mark's method to judgments about maximum distance that participants could walk along a narrow path. Replicating Mark, in Experiment 3 judgments were stable (across judgment trials) in the absence of added weight but improved when participants wore added weights at the torso, or at the ankles (cf. Ramenzoni, Riley, Shockley, & Davis, 2008). That is, participants learned about their changed affordance for walking despite having neither practice walking with the weights, nor feedback about judgment accuracy. Thus, on land (Experiment 3), our results resembled those reported by Mark (1987; Mark et al., 1990), extending their method for studying perception of the affordance for sitting to perception of affordances for walking. In Experiment 4, on a ship at sea, we observed a similar effect when participants did not wear added weight, suggesting that our nautical walking tasks was novel to our participants.

Mark et al. (1990) showed that improvement in judgments over a series of judgment trials depended upon the availability of ordinary body sway during judgments. That is, body sway appeared to serve an exploratory function, generating information that was sufficient for perception of affordances for sitting. Stoffregen et al. (2005) and Yu et al. (2011; cf. Mantel, Stoffregen, Campbell, & Bardy, 2015) showed that learning was, in fact, related to quantitative details of postural movement. Taken together with our results, these findings motivate future research that includes measurements of postural activity during judgments of walking ability on land, and at sea. Several studies suggest that information about walking ability might be related to the degree of multifractality of sway (Hajnal, Clark, Doyon, & Kelty-Stephen, 2018; Palatinus, et al., 2014).

We can regard the present study as being qualitatively similar to Experiment 3 from Mark et al. (1990), in which body sway was supplemented by walking (in relating to judgments about sitting ability). In future research, it will be important to replicate the present study but without including stepping in place. That is, participants should make judgments of walking ability without any exploratory movement, other than standing body sway. Such a study, without stepping in place, would be qualitatively similar to Experiment 4 from Mark et al., in which body sway was the only available type of movement.

Affordance categories?

Some researchers often have suggested that affordances naturally fall into separate categories (e.g., Fajen & Matthis, 2011). Affordances that are influenced by relatively static, or geometric properties of the body, such as leg length (e.g., Mark, 1987; Warren, 1984, Experiment 1), and shoulder width (e.g., Warren & Whang, 1987) are often referred to as 'body scaled affordances.' Affordances that are influenced by dynamic properties of the body such force production, energy efficiency (Warren, Experiments 2 and 3), or running speed (Oudejans et al., 1996) are often referred to as body-scaled affordances. However, this categorization has been empirical rather than theoretical, or *a priori* (e.g., Pepping & Li, 2000). In fact, in physical terms *static* and *dynamic* are not mutually exclusive; rather, static properties are a limiting case of dynamics (see Day, Wagman, & Smith, 2015). Of equal importance, affordances can be influenced by either (or both) static and dynamic properties of the environment, such as the width of an aperture (e.g., Higuchi et al., 2006), or the trajectory of a ball in flight (Oudejans et al.). The formal vacuity of a body-scaled versus action-scaled dichotomy is reflected in experimental research showing that affordances that have been formalized in geometric terms (i.e., relatively static body properties, such as leg length) also are constrained by dynamical properties (i.e., such as metabolic efficiency, muscle strength, and joint flexibility; Konczak et al., 1992; Snapp-Childs & Bingham, 2009; Warren, 1984). Similarly, properties of the body that are static (in the sense of being relatively persistent), in and of themselves, exert influence over action capabilities through their impact on body movement. The present study offers additional evidence that the categorization is misleading, and may be entirely fictitious (cf. Franchak et al., 2012; Day Wagman, & Smith, 2015). More specifically, the empirical distinction between body-scaled and action-scaled affordances is an artifact, or reification of the *a priori* hypotheses and experimental methods that have been studied, and the experimental methods that have been employed (e.g., Fajen, 2013; Warren & Whang, 1987).

Conclusion

In two experiments, weights added to the body at the torso, or at the ankles yielded dynamic consequences for walking (lateral foot placement). Affordances related to the weights were detected prospectively, in the absence of either walking practice, or feedback about the accuracy of judgments. On land, judgments were stable across trials in the baseline condition with no added weight, reflecting participants' typical walking ability. With added weight, initial judgments underestimated actual walking ability but, over the series of eight judgment trials judgments gradually increased in the direction of accuracy. At sea, initial judgments without added weight were underestimates, but again gradually increased over the series of judgment trials, suggesting that our task was novel even for experienced maritime crewmembers.

The results of the two experiments are consistent with the hypothesis that non-performatory movements, made before participants provided judgments, generated information about how the weights changed walking ability, and that participants' prospective judgments were informed by this self-generated information (cf. Mark, 1987; Mark et al., 1990). In Experiment 4, this was true despite the fact that both judgments and actual walking occurred in the presence of complex, multidimensional oscillation of the ground surface (a ship at sea). Overall, our results suggest the presence of robust, prospective sensitivity to the dynamic influence of added weight on affordances for walking.

CHAPTER V: General Discussion

In this study, I investigated if humans could perceive affordances at sea, if the perception would be changed by different sea conditions, and if constraints on the perceiver (weights) would change the perception as well. As stated in the introduction, I forged three goals and four hypotheses to be investigated by the end of my experiments.

Goal 1

The first of my three goals was to investigate how the walking direction on the deck of a ship influences participant walking affordances. Walter et al. (2017) was designed specifically to investigate this goal by utilizing a design that looked at perception of affordances in each direction immediately following one another. This was done in order to show that, even in the same weather conditions, the direction was in fact an influencing factor in the perception of affordances. Walter et al. (2019A) worked to replicate this result over a period of two days, with different weather conditions and therefore different ratios of ship angular motion. The outcome of Walter et al. (2019A) confirmed that walking direction on the deck of a ship does influence walking affordances, no matter the pattern of angular motion.

Simply stated, the design of the ship is enough to elicit differences in perception. These two experiments also confirmed my first hypothesis: Participants will be prospectively sensitive to the changes in affordances for walking along a narrow path caused by the differences in angular motion due to walking direction.

Goal 2

The second of my three goals was to study how sea condition influences affordances for walking. Walter et al. (2019A) was able to gather data over two different days with different sea conditions. Not only were there differences in the intensity of pitch and roll but also the ratio of these two movements. Excitingly, results of this study indicate that participants were indeed able to detect the differences that were attributed to the sea condition's influence on angular distribution.

Walter et al. (2019A) was also able to confirm my second hypothesis*:* H2: Participants will be prospectively sensitive to the changes in affordances for walking along a narrow path caused by changes in angular motion in the case that roll is greater than pitch. Since ship design creates an environment where pitch is usually more common that roll, this situation was important to highlight due to its rarity. Not only were participants sensitive to the changes in sea conditions between days, but were also sensitive to the changes that occurred due to this more uncommon situation.

Goal 3

My final goal was to study how sudden changes to the participant's properties influence the affordances for walking. Unlike previous goals, this one focused on changes to the animal rather than the environment. In Walter et al. (), weights were added to the participant in order to change their center of gravity, which was predicted to influence their walking ability (and therefore their perception) on the deck of a ship.

The results of this study were that overall mean judgments differed between the weight conditions and reflected actual differences in (subsequent) walking ability. These results also confirm my third hypothesis: participants will be prospectively sensitive to the changes in affordances for walking along a narrow path caused by the addition of weights. The final hypothesis proposed at the start of this dissertation was that the accuracy of judgments would increase across judgment trials without walking practice or feedback with the addition of weights. In Walter et al. (2019B), we found that walking in place (not walking the paths as practice) was sufficient to improve accuracy over the judgment trials. These results are similar to those seen in Mark (1990) and warrant further exploration in future experiments.

Significance

In terms of general affordances, walking at sea requires dynamic regulation of human movement, which is much more demanding than walking on land. The process of adapting and identifying affordances is not often seen in such a context, since land experiences rarely provide six degrees of freedom. To my knowledge, these experiments are the first of their kind and indicate a sensitivity to affordances in this dynamic environment. These experiments indicate that ship motion in the athwart and fore aft directions created differential affordances for locomotion, which were accurately detected.

The third study, which utilized weights to alter the participants' physical characteristics, provides further evidence that the difference between body-scaled and action-scaled affordances appear to be misleading. Previous research indicated that this categorization of affordances based on time-scale was a useful distinction to help our understanding of the nature of affordances. However, such an environment can have dynamic factors (ship motion) affecting static factors (human movement). Dynamic environments cause consistent fluctuations in the affordance equation, and humans are still able to adapt successfully. That is to say, the separation between static and dynamic properties is not as dramatic as one thought. These experiments allowed us to track the development and changes in affordances as a function of sea state, direction, and weight distribution which furthers our understanding of the dynamic systems that influence human behavior and the dynamic responses needed to successfully thrive in such an environment.

Application

By investigating the effect of direction on nautical affordances, human performance issues can be addressed in terms of workstation placement and overall design of the ship. Understanding the effects of direction and angular motion allows us to design a safer nautical environment. A better understanding of how humans interact with the ever-changing environment may also provide insight into human motion on land and in similarly dynamic environments, such as space. My additions to our understanding of affordances in such a demanding environment can be directly applicable into the design of workstations and general layout of nautical vessels. Understanding the directional differences allows for a safety measures to be further utilized, such as increased railings in the athwart direction both on deck and within the ship interior. As discussed in the previous chapter *Why Nautical?,* 80% of injuries on a single cruise ship occurred due to trips and falls, and were often times located within cabins. I firmly believe that, utilizing the outcomes of my research, a safer environment can be designed for any naval vessel. Having this knowledge may also help better prepare novices who are unaware of the forces at play when on a ship. Anecdotally, many of the experienced mariners in all three of my studies indicated verbally that there would be no difference of direction before judgments occurred. By informing the crews and passengers of the results and possible changes they may experience may decrease the number of injuries that any ship may experience.

Suggestions for Future Research

My experiments shed light onto the factors that influence human perception at sea, which will serve as a springboard for many future nautical studies. In future research, it will be important to track simultaneously changes in affordance perception and changes in the kinematics of posture and gait. Such coordinated monitoring can help us to understand how it is that participants learn about changes in affordances that emerge from the dynamics of ship motion (cf. Mark, 1987; Mark et al., 1990; Yu et al., 2011). Understanding how behavior occurs in these unique environments is extremely important to safety, but the completion of this research will not enlighten the entire field of nautical affordances. Since affordances utilize the collection of information, removing one form of information may provide unique results. The removal of visual information in reference to ship motion could simply be conducting these experiments inside the ship, where the horizon is not visible. If an individual is unable to properly detect their affordances, the risk of injury can increase substantially. Such research could have heavily implications for safety in both professional and leisure environments. The success of these studies also supports the investigation of affordances that are related to other forms of travel, since weather conditions and craft design may also influence the perception of affordances in these other environments.

Additionally, different populations tend to have different body modulation patterns. Old adults tend to sway more than healthy young adults (Stoffregen, 2016), which indicates that there may be differences in other kinesthetics between young and old populations. With the rise of the “senior cruise,” investigating how affordances differ between the young and old in these dynamic environments may be a fruitful route to pursue. Additionally, Stoffregen (2016) hints at the potential benefits of senior cruises, which requires greater adaptability in moment-to-moment posture and gait control. Investigating the development of affordances in the elderly at sea may provide insight into potential movement therapy options on land, which would be extremely beneficial with the rise of the elderly population seen in the US.

Finally, a better understanding of how novices perceive affordances in such dynamic environments is a springboard for research concerning “sea legs,” which has not yet been kinesthetically defined. All of the nautical studies discussed above used experienced crew members as participants, which can create difficulties in assumptions surrounding a general population and, therefore, provides justification for the study of novices. As briefly discussed above, the period of adaptation at sea (i.e., “getting your sea legs”) may provide unique insights into affordances that cannot be achieved on land. It should also be noted that the development of sea legs appears to be an extended process for most, which indicates that a study focused on affordances could reasonably provide insight into the time course of this scientifically neglected phenomenon. These possibilities are prime for investigation.

Conclusion

In conclusion, the theory of affordances has helped redefine how we approach human behavior through a paired understanding of the human and the environment. A variety of research has strongly supported the use of affordances to better examine human motor behavior through many different ages and environmental situations. Despite this, the investigation into nautical research has been nonexistent until the last ten years. Not only does this leave large gaps in the literature for affordances in dynamic, six degrees-of-freedom environments, but I believe more general understanding of human affordances can be achieved through research conducted at sea.

The results of my research have supported the hypotheses proposed at the introduction of this dissertation. Not only were experienced mariners sensitive to changes in affordances caused by direction, but they were able to detect differences between angular motion/days. Additionally, mariners were successful in detecting how their static, but newly changed properties (added weights) might influence their affordances in dynamic environments. Finally, the final hypothesis did have some merit, with accuracy improving in the no-weight condition. Overall, these studies have laid the groundwork for many more investigations concerning nautical affordances.

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Appendix I

Informed Consent Form

Human Subjects Code # 0711S21081

CONSENT FORM
Getting your sea legs

You are invited to be in a research study how people adjust to motion of a ship at sea. You were selected as a possible participant because you are a healthy adult, you are not pregnant, and you have no history of dizziness, seizures, balance disorders, or vestibular dysfunction. We ask that you read this form and ask any questions you may have before agreeing to be in the study.

This study is being conducted by Thomas A. Stoffregen, Professor, School of Kinesiology, University of Minnesota.

Background Information: The purpose of this study is to understand the process of adaptation to ship motion. This study focuses on how people control the body on ships at sea, and how ship motion affects subjective experiences, including perceived stability, and seasickness. Not everyone is susceptible to seasickness, and we do not expect everyone in this study to become sick.

Procedures: If you agree to be in this study, we will ask you to do one or both of the following things.

1. You will be asked to provide information about your current level of seasickness symptoms. You may be asked to participate in testing sessions before boarding, each day at sea, and immediately after disembarking from the ship. For studies of standing posture you may be asked to stand on a force plate, a device that measures body sway. For studies of gait you may be asked to insert sensors into your shoes that record your steps. Additional receivers may be attached to your skin at the base of your neck, using cloth medical tape, to your clothing at the hips and ankles, using Velcro straps, or to your wrists and ankles using snug straps. We will then ask you to stand and look at targets on a computer monitor, or to walk back and forth along a measured section of the dock or deck. If you experience motion sickness symptoms, you will be asked to report them immediately. In each test session, you will be asked to complete a total of up to 13 trials. Each trial will last 1 minute. Each day, you will be asked to state whether you are sea sick, and to report on the level of your seasickness symptoms. If you experience symptoms during a test session, the session will be discontinued immediately. The total duration of each test session will not exceed one hour.
2. You will be asked to give numerical ratings of your perceived bodily stability and your awareness of ship motion, as well as your current level of seasickness symptoms. You will then be asked to close your eyes and stand with your feet together or in “heel to toe” configuration; the experimenter will measure how long you can stand before you need to open your eyes or take a step.

Risks and Benefits of Being in the Study: The study has no risks. The risk of seasickness is inherent to travel on ships and is not caused by the research.
There are no direct benefits to participation.

Compensation: You will not receive any monetary compensation for your participation.

In the event that this research activity results in an injury, treatment will be available, including first aid, emergency treatment and follow-up care as needed. Care for such injuries will be billed in the ordinary manner, to you or your insurance company. If you think you have suffered a research related injury, let the ship's physician know right away.

Confidentiality: The records of this study will be kept private. In any sort of report we might publish, we will not include any information that will make it possible to identify a subject. Research records will be kept in a locked, password protected file; only researchers will have access to the records.
Voluntary Nature of the Study: Your decision whether or not to participate will not affect your current or future relations with the University. If you decide to participate, you are free to withdraw at any time without affecting those relationships. You will receive the same payment regardless of when you choose to withdraw.
Contacts and Questions: The researchers conducting this study are Thomas A. Stoffregen, Ruixuan Li, and Hannah Walter. You may ask any questions you have now. If you have questions later, you may contact them at the Affordance Perception-Action Laboratory, University of Minnesota. Phone: (612) 624-1025.

If you have any questions or concerns regarding this study and would like to talk to someone other than the researcher(s), contact Research Subjects' Advocate line, D528 Mayo, 420 Delaware Street Southeast, Minneapolis, Minnesota 55455; telephone (612) 625-1650.

You will be given a copy of this form to keep for your records.

Statement of Consent:

I have read the above information. I have asked questions and have received answers. I consent to participate in the study.

Signature ____ _ Date _____________

Signature of Investigator _______________________________________ Date _____________
Version: November 14, 2012